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PhD in Architecture and Design
Curriculum Architecture

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Optimization for Sustainable Design through Building Information Modeling

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The research is within the construction sector and wants to verify the existence of its real sustainability-oriented renewal. The research work proposes an investigation on three key topics: sustainability, digitization, and optimization. The main focus is to explore these three fields in order to understand possible virtuous complicity between sustainable development goals and the potential of the recent digital revolution, supported by the operational characteristics of optimization methods.

This work is intended as a contribution to limit the environmental impact and, if possible, reverse the dangerous trend of climate change. The evolution of human activities has produced substantial changes in the environmental system over time, influencing the climate and producing a rise of about 1.0°C in global temperature above pre-industrial levels. More than thirty years after the definition of sustainable development and after the first reflections on the need to change the conditions for the growth of human civilization, the negative trend of climate change has not been stemmed. Unfortunately, there is not much more time left to reverse it. Many construction experts are aware they have to take into account environmental, social, and economic impacts throughout the entire life cycle of construction, but we are still at the beginning of a real change of sustainable consciousness. A substantial transformation of the "mentality" is therefore necessary.

The digital revolution could represent a real "tool" for a profound renewal oriented towards sustainability. The digitization and extraordinary technological advances are changing our society and reducing the gap between the digital world and the physical world. This radical transformation is identified as the "Fourth Industrial Revolution". Compared to the previous three, it has a higher speed of progression and a more significant impact on different human activities. The construction, sector although lagging behind other sectors of human activity, is facing the challenge of entering the era of digitization following the principles of "Industry 4.0" in all its phases: production of materials, design, project execution, post-release moniotirng. Several new technologies are already available in the Construction 4.0 panorama and applicable to all phases of the construction process.

Thanks to the exponential increase in computing power, there is also rapid development in the field of optimization techniques and of tools in the design process. This new condition offers designers the opportunity to make increasing use of the decision-making processes in the complex world of construction in order to find optimal solutions, including those relating to sustainable goals.

The synergy between all these studied elements has generated reflections then translated into an operational strategy that could be a concrete demonstration of what is proposed and offered designers. In the last part of the thesis are then reported some applicative examples of the developed procedure to show the possible uses in the case of different objectives, digital models, tools, and calculation methods.

ABSTRACT

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1 INTRODUCTION

1.1 Research Areas of Interest

More than thirty years after the definition of the concept of sustainable development[1] and the first forecasted scenarios for our future, the impacts on the environment resulting from the evolution of human civilization are unchanged, if not worsened. Agenda 2030[2] renews the commitment to “protect the planet from degradation, including through sustainable consumption and production, managing its natural resources sustainably and intervening urgently on climate change, so that it can support the needs of generations present and future”.

Global warming, sea levels rise, and desertification are some of the most worrying impacts of climate change that are compromising the survival of many biological systems on our planet. To these must be added the inevitable effects due to the increase in world population[3] and the growth of existing urban areas or the creation of new ones[4].

Therefore, climate change mitigation is one of the most significant challenges of our time, and all sectors of human activity are called upon to make their contribution. The construction sector can make an essential contribution because its environmental, social, and economic responsibilities and implications are significant. There is a renewed call for an approach that takes account of environmental impacts, from the design phase to the demolition/recycling phase. Designers are called to move in a context for a resilient future where resources (energy, raw materials, economic, etc.) are limited and where we must, therefore, try to make optimal use of them.

The construction sector is facing another major challenge: entering the age of digitization, with rapid alignment with industry 4.0[5] principles in produc-

1 “Sustainable development is one that meets the needs of today without compromising the ability of future generations to meet their own needs”. This definition was first written in the 1987 “Brundtland Report” by the World Commission on Environment and Development (WCED).

2 Agenda 2030 for Sustainable Development is a programme of action with 169 goals articulated in 17 objectives for people, the planet and prosperity signed in September 2015 by the governments of the 193 UN member countries.

3 United Nations, Department of Economic and Social Affairs, Population Division, 2017. World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248.

4 Goal 11 of Agenda 2030 for Sustainable Development states that 60% of the world’s population will live in urban areas by 2030.

5 In 2011, three members of the German Federal Government’s Scientific and Economic Research Union presented the “Industry 4.0” concept at the “Hannover Mess” event.

tion, construction, and management processes. It is a challenge that involves all areas and all companies, from the smallest to the largest, offering new opportunities for growth and innovation. It is an opportunity of renewal for a sector that has always been a protagonist of "delayed innovations" compared to other fields of human activity. The need for safety, procedural checks, and specific regulations, the limited diffusion of "novelties", but above all its intrinsic inertia due to massive and traditional connotations, have regularly characterized this sector, especially in countries like Italy so rich in history.

The situation is evolving in a new and fast way linked to two new conditions: on the one hand, there is an increasing demand for innovative "tools" that lead to design their intelligent use for buildings, districts, and entire cities; on the other hand, there is a growing need to create (or perhaps better recreate) the conditions of well-being for man and to contribute to environmental quality actively.

The digitization of the construction sector is only just beginning. Small improvements will translate into substantial benefits for companies and society[6], including increased productivity, management of processes with greater complexity, time optimization, increased quality, and safety, etc. Digital technologies and methodologies are multiple and apply to all phases of the construction process: from planning, design, and construction to demolition or recycling/reuse. In many contexts related to construction, the focus of the digital transformation coincides with a specific "environment", BIM (Building Information Modeling), a parametric system able to ensure the full sharing of information of the entire process and coordination between all people involved.

Building Information Modeling is not only technological innovation but is a new approach to the entire life cycle of construction, capable of generating a real cultural revolution in our sector. The key is the information that each person involved in the process generates, manages, and stores, and which is now collected and put into a single central database. Thanks also to the renewed dynamics of collaboration and dialogue between all participants, BIM can generate multiple benefits for the entire construction chain in terms of productivity, quality, and safety.

6 Gerbert, P., Castagnino, S., Rothballer, C., Renz, A., Filitz, R., 2016. Digital in engineering and Construction. The Boston Consulting Group.

1.2 Research Aims

Climate change is one of the most significant challenges of our time. For several decades there has been an awareness of the urgency of the problem and the need for action. Although many plans for sustainable development, mitigation, and adaptation have been made over the years, the situation in the construction sector is almost unchanged, and there is still much room for improvement.

Simulation and validation of the final construction performance for the achievement of sustainability objectives could be done through the wide variety of existing tools. Their use, on the other hand, is not taken for granted or widely used in projects and, even if they are used, often occurs in phases after the design phase, when the possibilities for further changes are drastically limited.

Therefore, a substantial transformation is needed to change established practices in order to reverse the current course and achieve the objectives of sustainable development. The digital revolution, which is transforming all industrial sectors and has also reached the construction sector, could be a suitable opportunity for a profound renewal oriented towards sustainability. The new digital technologies and the increased computing power available today are useful to manage the increasing complexity and information in projects and can support collaboration and communication between the many designers involved.

The aim of the thesis is to analyse the current state of digitization in the construction sector, identify signs of change and seize the cues to propose a virtuous complicity between sustainable goals and the potential of the digital revolution; complicity enhanced by the operational characteristics of optimization methods. The further aim is to translate the synergy between the three key issues - sustainability, digitization, and optimization - through an operational strategy that can demonstrate the concrete applicability of what is proposed, up to the creation of an operational tool for designers.

1.3 Research Method

The research carried out was the result of a process of study, analysis, personal conceptual reflections and operational methodologies identified during the entire PhD period, which allowed to enrich and structure the research itself in an evolutionary process, until the achievement of the final objectives and the identification of the expected results.

The study and in-depth analysis of the state of the art of the three topics of investigation - sustainability, digitization, and optimization - is followed by a phase of dialogue and discussion with representative figures of different specificities and skills. A qualitative approach was chosen through semi-structured interviews with experts in the sector who could represent the different areas of the construction field. In this way, it is possible to collect information and to know different points of view useful to define state of the art in professional activity, and not only in research ones, concerning the three topics studied.

The previous phase of research and analysis also provided the necessary input to identify the strengths and weaknesses of the possible virtuous complicity between sustainability, digitization, and optimization. They were then put into practice through the identification of the proposed methodology, the description of its principles, and its possible applications, demonstrating that this useful complicity can be translated into something concrete and usable in the construction process. Finally, the methodology has been tested and validated on several implementations.

1.4 Research Boundaries

The first defined boundaries can be directly linked to the three main areas of research: sustainability, digitization, and optimization. The importance of the themes and their interdisciplinary nature has determined the need to give priority to certain aspects, in order to be able to deepen the research appropriately. It was therefore decided to focus attention on the definition of the state of the art of the three themes, circumscribing the study of the references to the last decade, thus reporting only a few historical hints and leaving more space for more recent sources and references.

The boundaries were then further delineated as the research progressed concerning the aims of the thesis. The decision to focus on sustainability has helped to filter further and select areas of research, leaving aside other aspects and potential arising from the combination of digitization and optimization in the construction sector.

Due to a further established boundary, chapters 2, 3, and 4 have a similar structure, which will be analysed in the following paragraph. In order to limit the scope of the research and its level of investigation, the focus on sustainability, digitization, and optimization has been carried out in a similar way. The study was divided into three levels ranging from general to particular: the framework of the theme, its reinterpretation in the construction field, and the analysis of a specific aspect.

Finally, further boundaries have been established for the application part dealt with in chapter 5. In this case, an inverse logic has been assumed, starting from some specific aspects to arrive at the global implications. The considerations and analysis of specific aspects and limited application examples have allowed the potential and implications of what has been studied to emerge in more general areas, not only strictly related to the achievement of sustainable development objectives.

1.5 Thesis Organization and Structure

The thesis is organized in eight chapters to bring out the themes, the reflections and applications studied, analysed, and developed.

The first chapter has framed the research conducted through the description of the scope, objectives, method used and research boundaries. Then three chapters follow - chapters two, three, and four - dedicated to the three critical concepts developed with the same key. These three chapters are structured similarly and presented with the same substructure articulated in three levels. A first paragraph that analyses the topic in cultural terms, a second paragraph that declines the topic in the construction sector, and finally, a third in which the peculiarities, concepts, and operational tools that will be used in the applicative part of the research emerge. Chapter five deals with the operational development of the thesis. Chapter six presents the concluding considerations concerning the research work developed and possible future developments in research. Finally, chapter seven deals with the appendix containing inserts on the most developed application parts; chapter eight consists of the references consulted for the work presented.

The general structure of the thesis is based on three analysed concepts: sustainability, digitization, and optimization. Each one has been studied in order to identify the principles, peculiarities, and tools to be used in the operational part of the research work. The schema shown in Figure 1 presents the analysis structure. The three words in evidence represent the three topics studied, and the concentric circles the three different levels of the analysis: general overview, specific overview in the construction field, and the final part "utility" contains the aspects used in the implementation. Finally, the three new points of view and concepts that emerge from the intersection of the starting words are shown in blue:

- the "sustainability 4.0" concept emerges from the re-reading of sustainability in construction 4.0 and its achievement thanks to the potential offered by the new tools and innovations introduced in the construction sector by digitization;
- "tools" are those identified in optimization and digitization research field and that will be used to meet the aims of the thesis;
- the "optimization goals" are those that are usually set to achieve the purpose of an optimization process and that are specifically identified in the field of sustainable design.

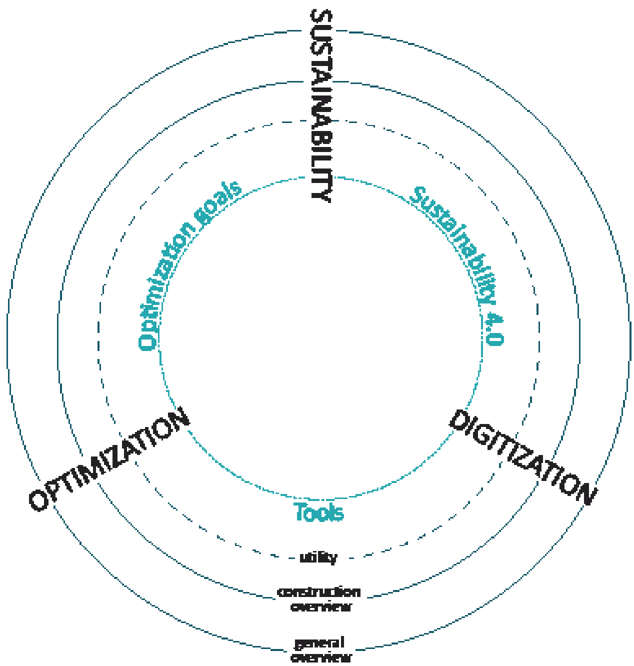


Figure 1 Structure of the thesis.

The evolution of human activities over time has produced substantial changes in the environmental system, influencing the climate and causing a rise of about 1.0°C in global temperature above preindustrial levels. According to the forecast scenarios, if the current rates of development are maintained, almost certainly, between 2030 and 2050, the increase will reach 1.5°C. More than thirty years after the definition of "sustainable development", contained in the report of the World Commission on Environment and Development, and the first considerations on the need to change the conditions for the growth of human civilization, the negative trend of climate change has not been curbed. Unfortunately, there is not much more time left to reverse it.

All areas of human activity are called upon to help limit the impact and, if possible, reverse the dangerous trend of climate change. The construction sector is undoubtedly one of the key players in this global challenge due to its extensive influence and its significant economic, social, and environmental implications. There are two main drivers: governments need to review and renew their current plans and outline long-term strategies; citizens demand and provide evidence that construction products and manufactured goods have high environmental performance. Therefore, architects and engineers are called upon to contribute actively to achieving this common goal by adopting a series of measures and criteria specific to sustainable design.

This chapter will, therefore, deal with the issue of sustainability. In section **2.1**, the current situation will be presented based on the latest data and the primary initiatives to tackle climate change will be given. Section **2.2** will then address sustainability in the construction sector, highlighting its implications and the current strategies used to achieve the common objectives. Finally, section **2.3** will describe the criteria proposed in sustainable design.

SUSTAINABILITY 2

2.1 Sustainable Development

"It's clear that business as usual simply isn't good enough anymore. We must do more – much more – in areas related to mitigation, adaptation, and the finance to support all of this work. And we must do it quickly."
(NDC Global Outlook Report 2019)

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs[1]. This definition is contained in the 1987 report of the World Commission on Environment and Development (WECD) commissioned to develop a global agenda for changing uncontrolled growth at the expense of the environment. It was realised in those years that there were limits to the economic/technological progress of human civilization[2] and that development could not be without the environment[3]. The scenarios, developed by researchers and international bodies, showed what would have happened to our planet if development conditions had not changed, for example, in terms of the use of natural resources and air pollution.

More than thirty years later, the definition of sustainable development and the reflections on the conditions for the growth of human civilization seem more pertinent and appropriate to the current situation. We are facing a situation where "it's clear that business as usual simply isn't good enough anymore. We must do more – much more – in areas related to mitigation, adaptation, and finance to support all this work. And we must do it quickly"[4].

The climate is changing globally, and according to the IPCC - Intergovernmental Panel on Climate Change[5], this is mainly due to greenhouse gas emissions from human activities, in particular from the use of fossil fuels, agriculture, and various

1 World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford; New York.
2 Meadows, D. L., Meadows, D. H., Randers, J., Behrens, W. W., 1972. The Limits to Growth. Potomac Associates - Universe Books.
3 World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford; New York.
4 UNDP, 2019. NDC Global Outlook Report 2019. The Heat Is On. Taking Stock of Global Climate Ambition.
5 In 1988, IPCC — Intergovernmental Panel on Climate Change was created to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options. More information available on www.ipcc.ch
6 IPCC, 2018. Global Warming of 1.5°C. IPCC, Switzerland.
7 Paris Agreement, Decision 1/CP.21, paragraph 21.

land use. Climate change is having a variety of impacts on our health, ecosystems, and economy, often in interaction with other factors.

In 2018 the IPCC issued a special report[6] on the impact of global warming of 1.5°C at the request of the 21st Conference of the Parties of the United Nations (COP21)[7]. The report provides a graph showing the trend of global warming from 1960 to 2017 and then estimates the future trend up to 2100 (Figure 2). More specifically, the study notes that human activities have caused about 1.0°C of global warming above pre-industrial levels, with a probable range from 0.8°C to 1.2°C and that the 1.5°C figure will almost certainly be reached between 2030 and 2050 if it continues to increase at the current rate.

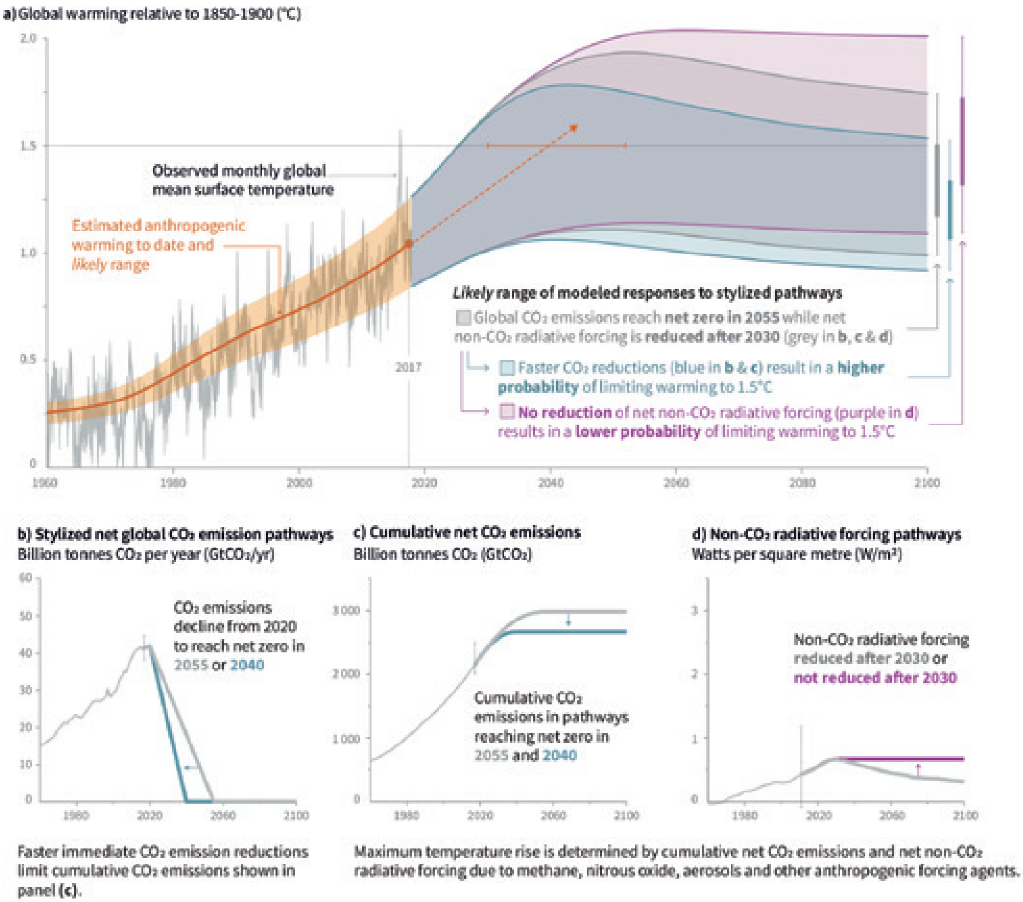


Figure 2 Observed global temperature change and modelled responses to stylized anthropogenic emission and forcing pathways (IPCC 2018).

In the 2019 "Emission Gap Report"[8] prepared by UNEP[9], similar results are reported. Figure 3 shows that greenhouse gas emissions have increased steadily over the last 30 years at a rate of 1.5% per year over the last decade. Between 2014 and 2016, there was a brief sign of stabilisation, and then in 2018, the record level of 55.3 GtCO2e was reached. The figure shows that the most significant contribution is due to fossil CO2 emissions from energy use and industry.

Figure 4 shows the specific trend of the top CO2 emitters: China, EU28, India, the United States of America, Russia, and Japan. The first four listed are responsible for 55% of total greenhouse gas emissions. If other countries and international transport are included, the value of 65% is reached. As Figure 4 shows, all trends are rising except for the US and the European Union. The US value has had a gradual decline in GHG emissions of 0.1% per year over the last decade, but a peak can be seen in 2018 due to increased energy demand following an unusually hot summer and a cold winter. The European Union's global greenhouse gas emissions have fallen steadily by more than about 1% over the last decade.

The situation changes, looking at the other part of the figure showing per capita emissions. Trends remain unchanged, but the contribution of individual states changes. There is a higher level for the US and Russia, and the lowest is in India and China is in fourth place just above European levels.

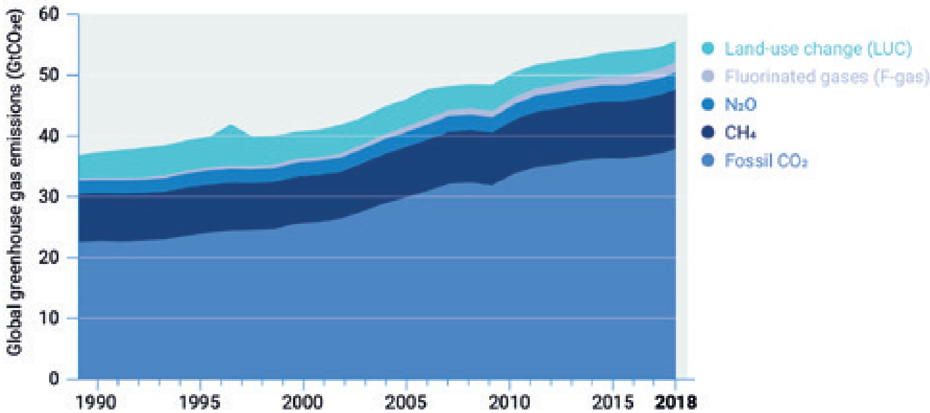


Figure 3 Global greenhouse gas emissions (UNEP 2019).

8 United Nations Environment Programme, 2019. Emissions Gap Report 2019. UNEP, Nairobi.
9 From 1972, the United Nations Environment Programme (UNEP) is the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system, and serves as an authoritative advocate for the global environment. More information available on www.unenvironment.org

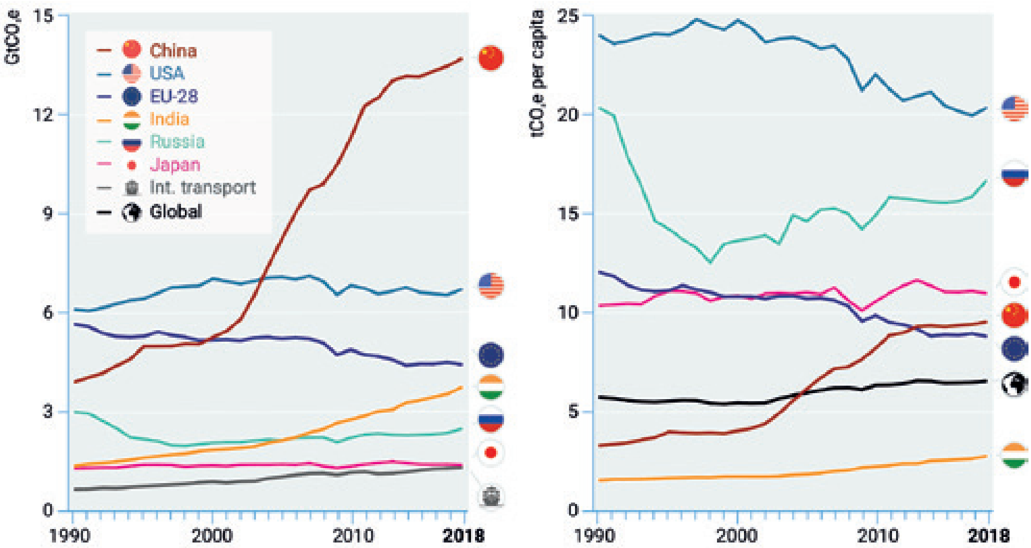


Figure 4 Top greenhouse gas emitters on an absolute basis (left) and per capita basis (right) (UNEP 2019).

All these studies outline future scenarios where it is highly likely that the situation will get worse with this trend, and impacts will become more severe in the coming decades. Hence the need to reduce greenhouse gases globally substantially in order to mitigate the impacts of climate change. At the same time, there is also a need to adapt, as it is not possible to prevent all impacts. In response to these two needs and to promote the society's growth in all sectors, plans and initiatives have been developed under the umbrella of sustainability.

2.1.1 Initiatives for Sustainable Development

The data reported in the previous paragraph and studies in this area suggest "rapid and far-reaching" changes in human activities. There are many initiatives aimed at promoting sustainable development that has arisen from the last decades of the last century until today. Only the main initiatives that belong to the most recent panorama and that concretely affect our daily life are reported.

Agenda 2030 The 2030 Agenda for Sustainable Development is an action program for people, the planet and prosperity signed in September 2015 by the governments of the 193 UN member countries. The 2030 Agenda renews the commitment to "protect the planet from degradation, including through sustainable consumption and production, managing its natural resources sustainably and intervening urgently on climate change, so that it can support the needs of generations present and future"[10].

The Action Programme contains 17 Sustainable Development Goals (SDGs) to be achieved by 2030 (Figure 5), which in turn are organised into 169 targets and over 240 indicators. The SDGs follow up on achievements of the Millennium Development Goals, that preceded them, and represent common goals on a set of critical development issues. "Common Goals" is a term used to underline that they concern all countries and all citizens: no one is excluded from them, nor should they be left behind along the path necessary to put the world on the road to sustainability. "The new agenda is a promise by leaders to all people everywhere. It is an agenda for people, to end poverty in all its forms – an agenda for the planet, our common home" declared Mr. Ban as he opened the UN Sustainable Development Summit, which kicked off today and wraps up Sunday.

One of the main innovations contained in this strategy is an integrated vision of the different dimensions of development. The unsustainability of the current model should not only be tackled on an environmental level, but also an economic and social level.

Figure 5 Sustainable Development Goals of the 2030 Agenda (UNDP 2015).

10 ONU, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. Resolution 70/1 of the General Assembly.

Agenda implementation requires the active involvement of all parts of society, from business to the public sector, from civil society to philanthropic institutions, from universities and research centres to information and culture professionals. All countries are called upon to contribute to the effort to bring the world on a sustainable path, with no longer any distinction between developed, emerging, and developing countries, even if the issues may differ according to the level of development achieved. This means that each country must commit itself to define its sustainable development strategy to achieve the SDGs, reporting on the results achieved within a process coordinated by the UN.

In 2019, "The Sustainable Development Goals Report 2019" was presented, showing the progress made based on the 17 objectives of Agenda 2030[11]. The report shows that there are improvements on some specific issues and some clear favourable trends at the country level, such as:

- from 2000 to 2017, the mortality rate of people under five years of age fell by 49% and extreme poverty decreased significantly, thanks to vaccination campaigns and the possibility for more and more people to access electricity;
- marine protected areas have doubled since 2010 and countries are working together to tackle illegal fishing;
- 150 countries have developed national policies to respond to the challenge of rapid urbanisation, and 71 EU countries now have policies and instruments to support sustainable consumption and production;
- numerous international organisations, companies, local authorities, scientific communities have engaged explicity with SDGs.

Despite this progress, the report identifies many areas of commitment that require urgent collective action. Some of these are:

- one million plant and animal species are at risk of extinction and the degradation of the territory continues unchecked;
- world hunger is on the rise and at least half the world's population lacks essential health services;
- more than half of the world's children do not meet reading and mathematical standards;
- only 28% of people with severe disabilities have received cash benefits;
- women in all parts of the world continue to face structural disadvantages and discrimination.

11 United Nations, Department of Economic and Social Affairs, 2019. The Sustainable Development Goals Report 2019. United Nations Publications, New York.

The most urgent area of intervention identified is climate change and the consequent need to reduce greenhouse gas emissions in order to avoid and reduce the catastrophic and irreversible effects that are already evident: the increase in ocean acidification, coastal erosion, extreme weather conditions, the frequency and severity of natural disasters, the continuous degradation of the territory. The IPCC special report on global warming[12] shows the interactions between SDGs and three sectoral climate change mitigation strategies (Figure 6):

- supply of energy such as biomass and non-biomass renewable energy, carbon capture, and storage with bioenergy or fossil fuels;
- energy demand in terms of, e.g. fuel switching and efficiency in transport, industry, and buildings;
- land use as food waste reduction, soil sequestration, livestock and manure management, reduction of deforestation.

The reported data show that in general, synergies are more significant than trade-offs in achieving climate change and SDGs targets. It also shows that energy demand mitigation strategies are more consistently and strongly associated with broader sustainability benefits. The key to achieving the objectives is a synergy between different strategies such as deep decarbonisation and SDGs[13]. Building on this principle, the strength of Agenda 2030 is to bring together heterogeneous groups to work towards common goals, through multilateral actions and global solutions.

Paris Agreement

In December 2015, the Conference of the Parties on Climate Change (COP21) was held in Paris, where a universal agreement on combating climate change was reached for the first time.
The Paris Agreement entered into force on 4 November 2016, thirty days after the date on which at least 55 Parties to the Convention, representing in total at least 55% of global greenhouse gas emissions, deposited their instruments of ratification, acceptance or approval. To date, 187 Parties out of 197 have signed the Agreement.

The central objective of the Paris Accord is to strengthen the global response to the threat of climate change by keeping the global temperature increase in this century well below 2°C compared to pre-industrial levels and continuing efforts to limit the temperature increase to 1.5°C further. Also, the Agreement aims to strengthen the capacity of countries to address the impacts of climate change.

12 IPCC, 2018. *Ibid*.
13 Hawksworth, J., Clarry, R., Audino, H., 2017. The World in 2050. Price water house Coopers.

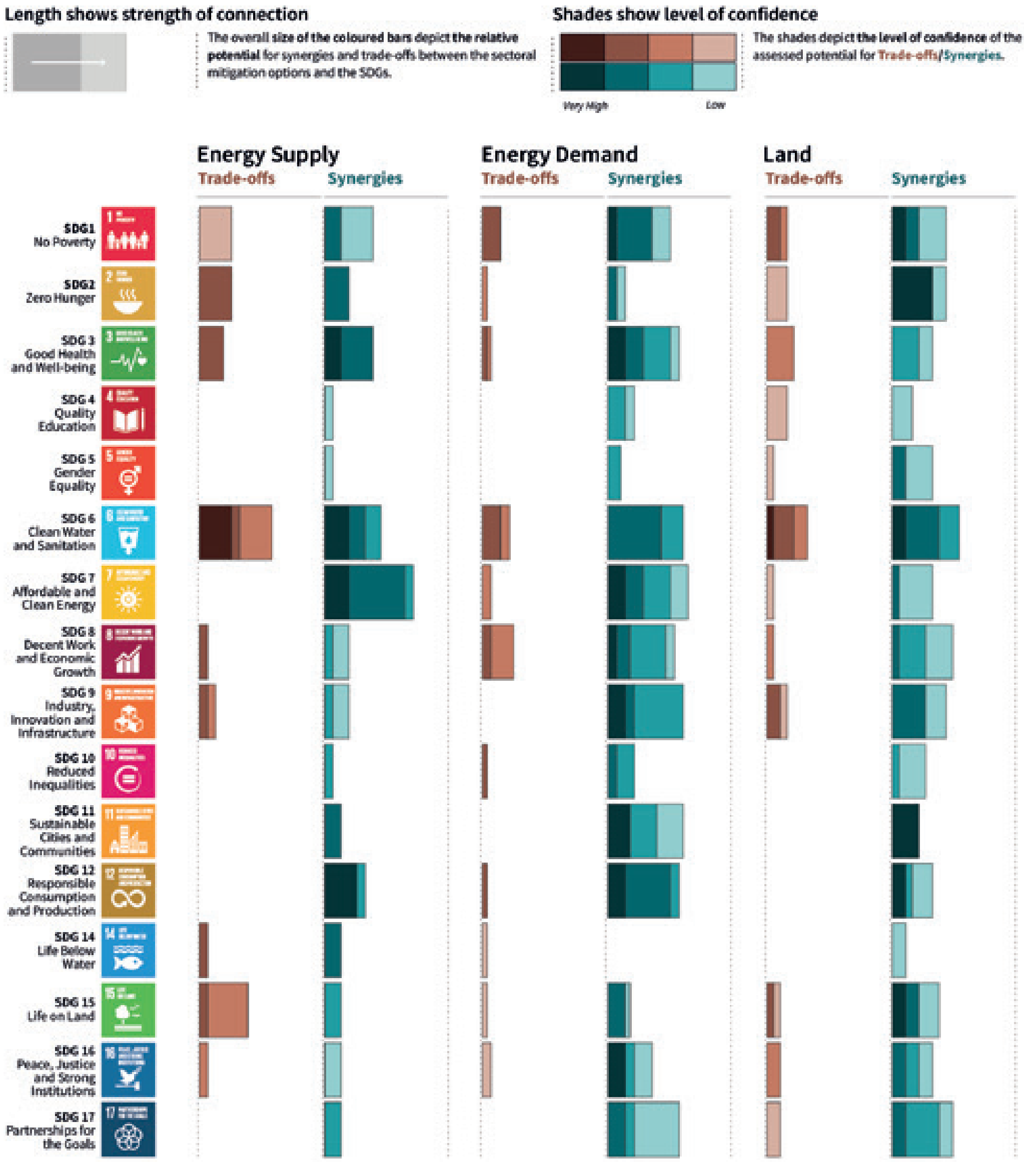


Figure 6 Indicative linkages between mitigation options and sustainable development using SDGs (IPCC 2018).

To achieve these ambitious targets, adequate financial flows, a new technology framework, and a capacity-building framework will be put in place, thus supporting action by developing countries and the most vulnerable countries in line with their national targets. The Agreement also provides for greater transparency of action and support through a more robust transparency framework.

The Paris Agreement brings all nations together in a common challenge to undertake ambitious efforts and combat climate change by adapting to its effects. Specifically, all parties are required to make the best efforts through nationally determined contributions (NDCs). This includes the obligation for all Parties to report regularly on their emissions and their concrete commitment to implementation. As with SDGs, the process will be monitored, and every five years, collective progress towards achieving the objective of the Agreement will be assessed.

NDCs are the critical elements of the Paris Agreement. They are plans established by each country for mitigation and adaptation. They contain strategies for reducing greenhouse gases and increasing resilience in the new world with more heatwaves, floods, droughts, fires, and more. So far, 184 nations have presented their first NDCs, and only two nations, Marshall Islands and Suriname, have prepared a second one[14].

In 2019 the UNDP[15] presented the first report on NDCs[16], which shows that there are currently 197 nations participating in COP21 (Figure 7):

- 75 countries, accounting for 37% of global greenhouse gas emissions, are revising their national climate program and plan to increase adaptation and mitigation efforts;
- 37 countries, accounting for 16% of global greenhouse gas emissions, intend to update their existing plans with new data, information and/or assumptions;
- of 71 nations, accounting for 21% of global GHG emissions, it is not clear how and whether they will revise their plans;
- finally, the remaining 14 countries, accounting for 26% of global GHG emissions, have no plans to revise their NDCs.

It is interesting to note that the first group of the 75 most advanced countries consists mainly of developing countries: it is among them that we find the only two na-

14 More information available on www4.unfccc.int/sites/NDCStaging/Pages/Home.aspx
15 The United Nations Development Programme (UNDP) is an international organisation created on 1 January 1966, following the resolution of the General Assembly of the United Nations (UN) of 22 November 1965. Nowadays, UNDP works in about 170 countries and territories, helping to achieve the eradication of poverty and the reduction of inequalities and exclusion.
16 UNDP, 2019. *Ibid*.
17 Information was not available for the remaining 58 (UNDP, 2019).

tions to have revised their plans for the second time. On the other hand, it can be seen that many of the developed countries, although they have yet to clarify plans for short-term NDC revisions, are mapping long-term plans to eliminate greenhouse gases by 2050 through the so-called Long-Term Strategies (LTS). The LTS provides, in most cases, a vision for a zero-carbon society to drive policy and stimulate innovation and investment in clean technologies to keep the planet safe. So far, 12 countries have submitted LTSs to the UNFCCC since 2016, 53 nations have indicated that they are planning LTSs, 44 nations plan to do so, and the remaining 31 nations have no plans to do so[17].

The key concept behind the Paris Agreement is that no country should backtrack on its stated objectives. Indeed all countries are called upon to present increasingly ambitious NDCs every five years. 2020 will, therefore, be a crucial year to analyse the validity of this mechanism and to get a picture of the progress achieved five years after COP21.

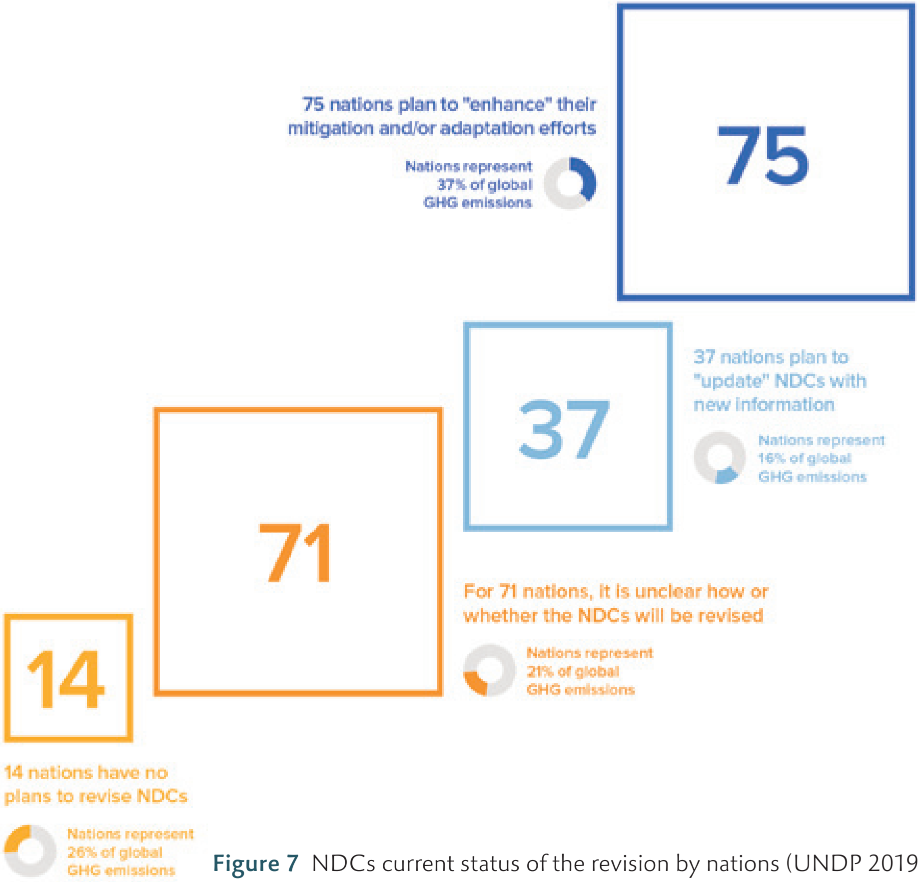


Figure 7 NDCs current status of the revision by nations (UNDP 2019).

EU climate strategies

Europe has long been fighting climate change by implementing policies in close cooperation with international partners and members of the European Community. Before joining and complying with recent global plans, several plans and directives defined the rules for European countries since the Kyoto Protocol.

The latest of these is the 2020 climate and energy package, which has been adopted by EU leaders in 2007 and enacted in 2009 to reduce greenhouse gas emissions by 2020. The package sets three key targets:

- 20% cut in greenhouse gas emissions (from 1990 levels);
- 20% of EU energy from renewables;
- 20% improvement in energy efficiency.

The Commission's website states, "EU is on track to meet the 20% emissions reduction target for 2020" and EU greenhouse gas emissions were reduced by 23% between 1990 and 2018, while the economy grew by 61% over the same period.

In October 2014, a new framework for 2030 was adopted by the European Council. The targets for renewables and energy efficiency were revised upwards in 2018. It is the new climate and energy framework that includes the following objectives for the period from 2021 to 2030:

- at least 40% cuts in greenhouse gas emissions (from 1990 levels);
- at least 32% share for renewable energy;
- at least a 32.5% improvement in energy efficiency.

The EU has adopted integrated monitoring and reporting rules to ensure progress towards the 2030 climate and energy targets and its international commitments under the Paris Agreement. Member States are obliged to adopt integrated National Climate and Energy Plans (NECPs) for the period 2021-2030. Member States had to submit their draft plans by the end of 2018. The final plans must be submitted by the end of 2019.

On 28 November 2018, give the UN climate summit (COP24) in Katowice, Poland, the Commission adopted its 2050 long-term strategy. It is a vision for a climate-neutral future that covers nearly all EU policies and is in line with the Paris Agreement objective to keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C. The strategy is presented in the document 28/11/2018 - COM (2018) 773 - A Clean Planet for all - An European strategic long-term vision for a prosperous, modern, competitive, and climate neutral economy.

A climate-neutral EU by 2050 can be achieved by investing in realistic technological solutions, empowering citizens and aligning actions in critical areas such as industrial policy, finance or research, while ensuring social equity for a fair transition. Seven strategic areas are identified:

- energy efficiency;
- deployment of renewables;
- clean, safe and connected mobility;
- competitive industry and circular economy;
- infrastructure and interconnections;
- bio-economy and natural carbon sinks;
- carbon capture and storage to address remaining emissions.

The documents of the 2050 strategy do not outline a detailed technical strategy and do not address the intermediate objectives towards the 2050 target. However, a clear message emerges from them that: "net zero" is necessary (in the context of the global fight against climate change), that it is possible (existing technology options can get us there), and that undergoing this transition is beneficial for Europe it could be the platform for a stronger, modernised economy.

Bottom-up initiatives

The Paris Agreement and the 2030 Agenda for Sustainable Development both represent universally endorsed political visions that mark a paradigm shift with a "top-down" approach of international mandates to nations and thus their citizens.

There are, however, several initiatives that follow the opposite path (bottom-up) made up of citizens and consumers who are increasingly aware and concerned about sustainability. They join forces and demonstrate to push governments and industries to accelerate the revolution of their processes and products towards ecological transition and sustainable development.

The urgency of the problem has caused protests and actions to spread, almost virally, and the promoters are mainly young people. In Italy, 85% of young people born after 1997 say they are concerned about environmental issues; 70% choose companies committed to protecting the environment; 82% are attentive to waste and 85% do a separate waste collection[18].

18 Data available on www.nomisma.it/servizi/osservatori/osservatori-realizzati-ad-hoc/genz-monitor/

Many initiatives have been launched in recent years to combat climate change. Among them, "Fridays for Future"[19] is the most successful and has spread with extraordinary speed thanks to the communicative power of social media. In August 2018, 15-year-old Greta Thunberg sat in front of the Swedish parliament every three weeks to protest the lack of action on the climate crisis and published what she was doing on Instagram and Twitter. The news has gone viral and has managed to reach some 13 million young people, and more, in 228 countries around the world (Figure 8).

"Let's Do it"[20] is another movement born in Estonia in 2008 and then spread all over the world. It promotes the actions of cleaning and reduction of waste production. Among the best-known initiatives and involving hundreds of millions of people around the world is "Cleanup Day"; its last edition was held on 21 September 2019. Following this initiative, there are many others at the local level or born from the will of small associations.

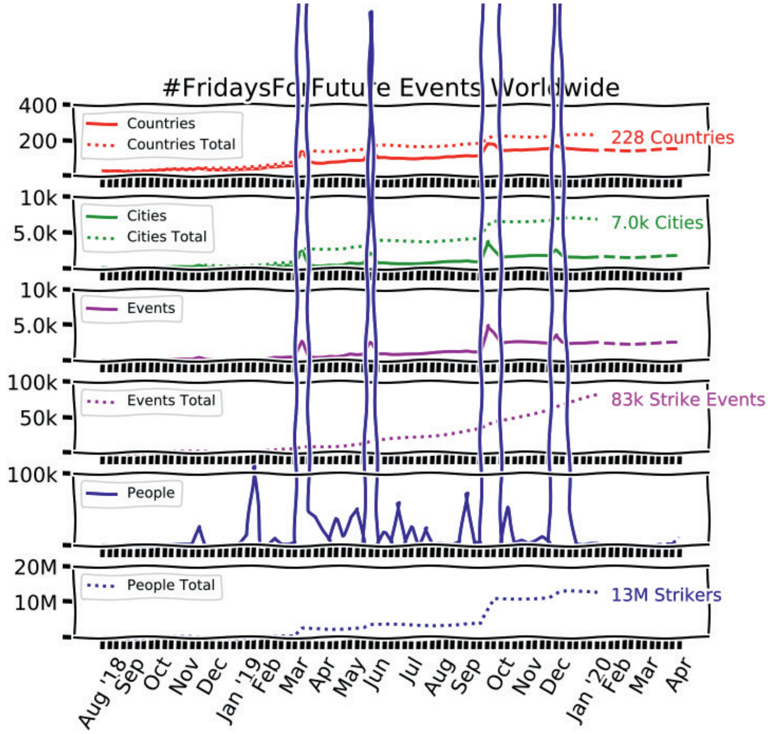


Figure 8 Fridays for Future events statistics updated on 15th January 2020 (www.fridaysforfuture.org).

19 Further information available on www.fridaysforfuture.org
20 More information available on www.letsdoitworld.org

2.2 Sustainability in Construction

The eleventh goal of Agenda 2030 is dedicated entirely to "Sustainable Cities and Communities". Cities are centres for new ideas, for commerce, culture, science, productivity, social development, and much more. However, this objective has been set because many challenges still exist today to maintain urban centres as workplaces and well-being places, while at the same time not damaging the environment and resources. In this programme for a sustainable future, as in other previous ones, the construction sector holds a distinguished place given its extensive influence and implications, which can be summarised in three macro-aspects: society, economy, and environment.

The world population will grow significantly to almost 10 billion people by 2050[21]. Today, half of humankind, about 3.5 billion people, live in cities, and by 2030, people are expected to move from the countryside to cities and around 60% of the world's population will live in urban areas[22]. 95% of urban expansion in the coming decades will take place in developing countries and today there are still more than a billion people living in slums, and the number, rather than decreasing, is continously increasing (Figure 9). Soon, it will, therefore, become increasingly important to ensure access to adequate, safe, and affordable housing and essential services for all.

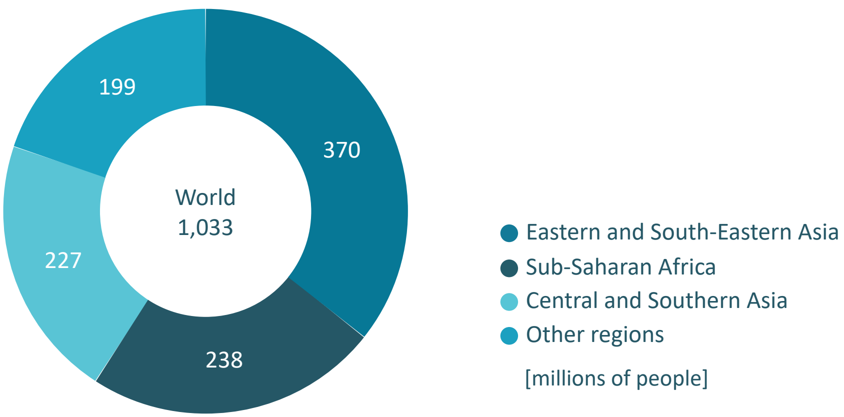


Figure 9 Urban population living in slums or informal settlements (UDNP 2019).

21 United Nations, Department of Economic and Social Affairs, Population Division, 2017. World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248.
22 Goals number 11, Agenda 2030 for Sustainable Development.

Moving towards cities will also lead to rapid urbanisation, which will affect the need for infrastructure, roads, freshwater supply systems, sewerage systems, public transport, etc. (Figure 10). To date, cities occupy only 3% of the earth's surface but are responsible for significant energy consumption and related carbon emissions. However, the growth of cities, if driven by inclusive and sustainable urbanisation and participatory and integrated planning and management capacity, can take advantage of the cities' high density to improve their efficiency and technological development, reducing resource and energy consumption.

For almost the entire population of the world, the built environment heavily influences the quality of life, as people spend an average of 90% of their time indoors. Therefore, the building and the materials used in it have an essential impact on the health and well-being of its occupants. The building is one of the first activities that humankind developed, and since then, it continues to shape our daily lives in unique ways. To quote Winston Churchill's famous statement: "We shape our buildings and, afterward, our buildings shape us".

The economic importance of the construction sector is based on the total annual turnover, which represents about 6% of world GDP[23]. Specifically, it accounts for 5% of total GDP in developed countries, while for developing countries it is over 8% of total GDP. The industry is expected to grow significantly in the coming years to

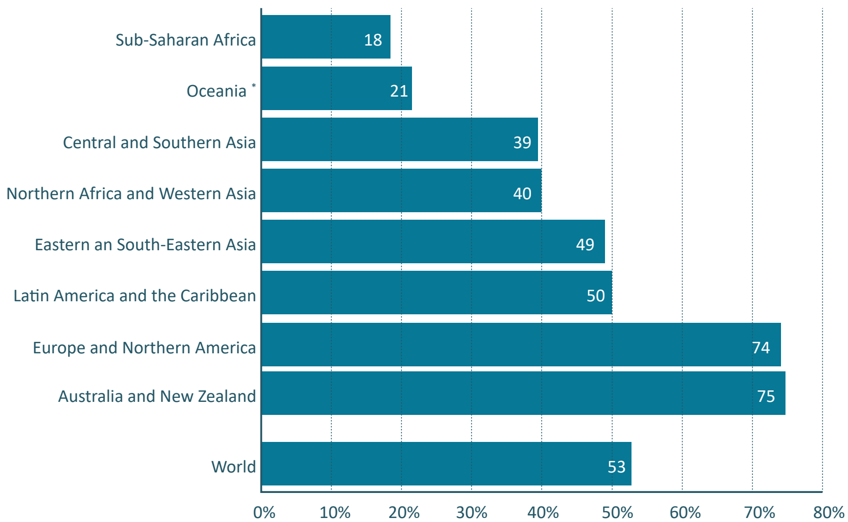


Figure 10 Share of population with convenient access to public transport (UNDP 2019).

reach an estimated revenue of $15 trillion by 2025, also creating new jobs and positions. To date, it is estimated that more than 100 million people are already employed in this sector worldwide.

The construction field can also be considered a “horizontal” industry serving all other vertical industries to provide and maintain housing, facilities, and infrastructure. Moreover, buildings are the place where almost everyone lives and works. For example, residential buildings account for 38% of the overall construction volume; transport, energy and water infrastructure for 32%; institutional and commercial buildings for 18%; and industrial sites (from cement to automotive production) for 13%[24]. The innovation of all industries and the different demands for space and infrastructure needed will also require renovation in construction.

Finally, given the characteristics and products of this industry, it is the one with the highest consumption of resources, raw materials, and waste production. Therefore, it has a substantial impact on the environment. It is estimated that it uses about 36% of total energy consumption with the consequent high release of CO2[25]. About 50% of solid waste in the United States comes from construction and demolition[26]; this value in Europe is 31%[27] and in Italy, about 41%[28].

All these data, collected from the most recent reports and statistics available, show that even small improvements in this area will result in substantial environmental and human benefits for business and society. Reducing waste would mean optimizing the use of natural resources and energy. Improving the whole process would reduce costs and resource consumption, improve the quality of construction and the quality of materials used, contributing to a healthier indoor environment and increasing sustainability.

Achieving these objectives is pursued at two levels: on the one hand, some governments undertake strategic and large-scale plans by directing the sector through the regulatory and legislative framework and at the same time supporting it through major investments; on the other hand, there are citizens who, by investing their savings in buildings, demand higher quality and performance also from view of sustainability. These two approaches, which we could call “top-down” and “bottom-up” respectively, will be discussed in the following paragraphs.

23 World Economic Forum, 2016. Shaping the Future of Construction. Switzerland, Geneve.
24 World Economic Forum, 2016. *Ibid.*
25 IEA, 2017. Energy Technology Perspectives 2017. IEA/OECD. Paris.
26 Data available on www.eesi.org/briefings/view/042214recycling
27 Fischer, C., Werge M., 2009. EU as a recycling society. Present recycling levels of Municipal Waste and Construction & Demolition Waste in the EU. ETC/SCP 2/2009, Copenhagen.
28 ISPRA, 2017. Rapporto rifiuti speciali 2017. Rapporti n. 265/2017. ISPRA – Settore Editoria, Roma. ISBN 978-88-448-0829-7.

2.2.1 Standards Framework

International climate negotiations and guidelines for tackling climate change are translated into directives, laws, and technical standards by individual countries. The framework is broad and complex because different aspects of sustainability are dealt with and there are many differences based on geographical scope, social context, building characteristics, construction techniques, etc.

In the European context from the new millennium onwards, there are several directives issued to outline a general direction for the Member States. They are then entrusted with the task of translating and implementing the concepts contained in the directives through national laws and regulations.

The European Commission began the process of construction sustainability by outlining the most significant rules with Directive 2002/91/EC Energy Performance of Buildings (EPBD), which is no longer in force since 2012. This Directive is a translation of the principles of the Kyoto Protocol for the European context and the specific characteristics of its construction sector. This document aimed to "promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness"[29]. Therefore, the Directive steered the sector towards energy efficiency and required the Member States to draw up their implementing measures.

In 2006, the European Directive 2006/32/EC of the European Parliament and the Council on energy end-use efficiency and energy services was drafted[30]. This Directive was valid until 2014 and defined the regulatory and operational framework to allow each Member State to achieve the energy end-use energy savings targets for 2015.

On 23 April 2009, Directive 2009/28/EC on the promotion of the use of energy from renewable sources was implemented[31]. It establishes a common framework for the promotion of energy from renewable sources. It also sets mandatory national targets for the overall share of energy from renewable sources in the final gross consumption of energy and for the share of energy from renewable sources in transport, as well as sustainability criteria for biofuels and bioliquids.

29 Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings.
30 Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC.
31 Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

In July 2010, Directive 2010/31/EU of the European Parliament and of the European Council on the energy performance of buildings, which updates and replaces Directive 2002/91/EC[32], enterd into force. It starts the recast of the so-called technical standards package supporting the EPBD.

On 25 October 2012, the European Union finally adopted the new Energy Efficiency Directive 2012/27/EU[33]. This concludes the legislative process of approval of the Energy Efficiency Directive, started by the European Commission in June 2011, with a proposal for a Directive containing legally binding measures to prescribe a more significant commitment of Member States to use energy more efficiently at all stages of the energy chain from its transformation to its distribution and final consumption.

The Directive is part of the 2020 Climate & Energy Package, with which the European Union has set itself the goal of achieving three crucial goals by 2020:

- the reduction of greenhouse gas emissions by 20% compared to 1990 levels;
- 20% of energy needs from renewable sources, i.e. increasing the use of renewable energy sources (wind, solar, biomass, etc.) and achieving a 20% share of renewable energy in total European energy consumption;
- the increase in energy efficiency that can be achieved by reducing energy consumption by 20%.

Finally, to complete the overview, EU 2018/844 was published in June 2018[34], making some amendments to Directives 2010/31/EU and 2012/27/EU still in force. This document stems from the need to outline a direction and new targets for member countries to promote the development of a sustainable, competitive, secure and decarbonised energy system by 2050 and to reduce greenhouse gas emissions by at least 40% by 2030. To this end, member states are asked to transpose and implement the requirements of the Directive by 20 March 2020.

Among the main new features are two key indications:

- requirement to improve the energy performance of new and existing buildings and to achieve strongly decarbonised building stock by 2050; to this end, member states are required to develop long-term national strategies to promote the efficiency of residential and non-residential buildings, both public and private, in order to reduce EU emissions (compared to 1990 levels) by 80-95%;

32 Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

33 Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.

34 Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

- a "smart building readiness indicator" is required to be introduced in national strategies to raise awareness among owners and occupants of the value of building automation and electronic monitoring of technical building systems and reassuring occupants about the real savings of these new improved functionalities[35].

Therefore, 2020 will be a milestone year for national building policies as they will be called to review and renew their regulatory and legislative framework.

Italian Framework The Italian national framework on the measures introduced by the directives on the efficiency and energy performance of buildings is made up of a series of laws that have followed one another since 2005 with the adoption of the first Directive 2002/91/EC.

"Decreto Legislativo 192/2005"[36] establishes the criteria, conditions, and methods for improving the energy performance of buildings in order to promote the development, enhancement, and integration of renewable sources and energy diversification. The subsequent "Decreto Legislativo 311/2006"[37], amended and strengthened various aspects of the previous one, for example:

- the obligation to certify the energy performance of buildings both in the case of sale and renting;
- the obligation to certify energy certification in contracts for the management of air conditioning systems in public buildings;
- limit values of the energy performance index for winter air conditioning (EPi) more restrictive than those of D.lgs 192/2005, diversifying them by S/V ratio[38], date of construction of the building, and climate zone to which it belongs.

In 2008, Directive 2006/32/EC was also implemented with "Decreto Legislativo 115/2008"[39], introducing the following points:

- simplified procedures for the installation of wind power plants with an overall height of no more than 1.5 meters and no more than one-metre diameter, solar thermal or photovoltaic systems adhering to or integrated into the roofs

35 Directive UE 2018/844. *Ibid.*
36 Decreto Legislativo 19 agosto 2005, n. 192. Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia.
37 decreto legislativo 29 dicembre 2006, n. 311 Disposizioni correttive ed integrative al decreto legislativo 19 agosto 2005, n. 192, recante attuazione della direttiva 2002/91/CE, relativa al rendimento energetico nell'edilizia.
38 The S/V ratio is calculated on the basis of the heat loss area (S) and the volume of the construction (V).
39 Decreto legislativo 30 maggio 2008, n. 115. Attuazione della direttiva 2006/32/CE relativa all'efficienza degli usi finali dell'energia e i servizi energetici e abrogazione della direttiva 93/76/CEE.

of buildings with the same inclination and orientation of the aquifer, and authorization for the construction and operation of cogeneration plants with a capacity < 300 MW;
- volumetric incentives for new buildings and derogations from border distances for new and existing buildings if there is a minimum 10% reduction in the energy performance index;
- public sector obligations about energy audits and certification for public buildings, purchase of energy-efficient appliances, systems and vehicles, use of financial instruments for energy saving;
- certification systems for energy management experts, energy management systems, and energy diagnostics.

The "Decreto del Presidente della Repubblica del 2 aprile 2009 n. 59"[40], which came into force on 25 June 2009, concerning the implementation of EU Directive 2002/91/EC on the energy performance of buildings, defined the criteria, calculation methods, and minimum requirements for the energy efficiency of buildings. The text sets minimum requirements for the energy performance of new and existing systems and buildings, confirming those already established in Annex I of D.lgs 192/2005, with the addition of the introduction of a maximum permissible energy performance value for summer cooling of the building envelope.

In the same year, "Decreto Ministeriale 26 giugno 2009"[41] issued the first national reference guidelines for the energy certification of new and old buildings and the definition of calculation methods definitively sanctioned the entry into force of energy certification on the entire national territory, introducing:
- a new energy class A+, to be added to the existing seven;
- a new energy classification, indicating the performance of the envelope (mandatory also in summer for buildings larger than 200 m^2).

On 29 March 2011, "Decreto legislativo 28/2011"[42] came in force, implementing Directive 2009/28/EC and defining the instruments, mechanisms, incentives, and institutional, financial and legal framework necessary to achieve the objectives for energy from renewable sources up to 2020.

40 Decreto del Presidente della Repubblica 2 aprile 2009, n. 59. Regolamento di attuazione dell'articolo 4, comma 1, lettere a) e b), del decreto legislativo 19 agosto 2005, n. 192, concernente attuazione della direttiva 2002/91/CE sul rendimento energetico in edilizia.
41 Decreto Ministeriale 26 giugno 2009. Linee guida nazionali per la certificazione energetica degli edifici.
42 Decreto legislativo 3 marzo 2011, n. 28. Attuazione della direttiva 2009/28/CE sulla promozione dell'uso dell'energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE.

The framework is completed more recently with “Decreto legge 63/2013”[43], later converted into Law 90/2019[44], concerning urgent measures for the implementation of Directive 2010/31/EU on the energy performance of buildings for the definition of infringement proceedings initiated by the European Commission, as well as other provisions on social cohesion. These dispositions were implemented with the publication of “Decreto Ministeriale 26 giugno 2015”[45] on the following three topics:

- minimum requirements and definition of the nearly zero-energy building;
- national guidelines for energy certification, classification methods and new template of energy performance certificate;
- new templates for the technical report.

Finally, the implementation of Directive 2012/27/EU on energy efficiency is delegated to “Decreto legislativo 102/2014”[46] and the additional and corrective provisions of to “Decreto legislativo 141/2016”[47], which contains new provisions on the energy performance of public administration buildings, energy audits, measurement and billing, efficiency funding and sanctions.

2.2.2 Assessment Tools

International Agreements, translated into standards and laws, are supported by systems for assessing the sustainability of buildings. These are voluntary certification systems which, based on a score assigned to specific pre-established indicators and using an evaluation scale usually organised in levels to be achieved, allow the quality of the construction to be measured.

The leading promoters of the dissemination and use of these systems are the customers themselves, given their voluntary and non-compulsory nature. The 2018 report on “World Green Building Trends”[48] confirms with the survey results that the main driver for sustainability-oriented building activities is customer demands (Figure 11).

43 Decreto-Legge 4 giugno 2013, n. 63 Disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010.
44 LEGGE 3 agosto 2013, n. 90. Conversione, con modificazioni, del decreto-legge 4 giugno 2013, n. 63.
45 Decreto del Ministero dello sviluppo economico 26 giugno 2009.
46 Decreto legislativo 4 luglio 2014, n. 102. Attuazione della direttiva 2012/27/UE sull’efficienza energetica, che modifica le direttive 2009/125/CE e 2010/30/UE e abroga le direttive 2004/8/CE e 2006/32/CE.
47 Decreto Legislativo 18 luglio 2016, n. 141. Disposizioni integrative al decreto legislativo 4 luglio 2014, n. 102.
48 Dodge Data & Analytics, 2018. World Green Building Trends 2018. SmartMarket Report. [online] www.construction.com/toolkit/reports

The reasons for this choice are many and can be attributed to three macro-aspects: social, economic, and environmental. From the social point of view, the primary trend detected in customers is to obtain buildings that guarantee better living comfort levels and improve the health of the occupants. Another reason that in past years was in the first place is to promote and encourage sustainable business practices (Figure 12). In terms of the economic reasons, the lowest cost in the management of the building comes first, followed by other reasons relating to the higher value of the property, which leads to higher income from its sale or rental (Figure 13). Finally, from an environmental point of view, in the first place, there is the possibility of reducing energy consumption, and from the graph, it can be seen that this reason has remained unchanged over the years (Figure 14). Then we find other reasons related to the reduction in the use of natural resources and water, the production of greenhouse gases, and the improvement of air quality.

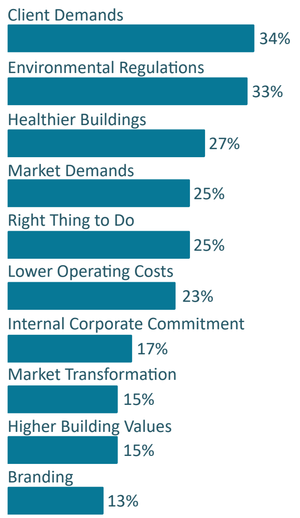


Figure 11 Triggers driving future green building activity (Dodge Data & Analytics 2018).

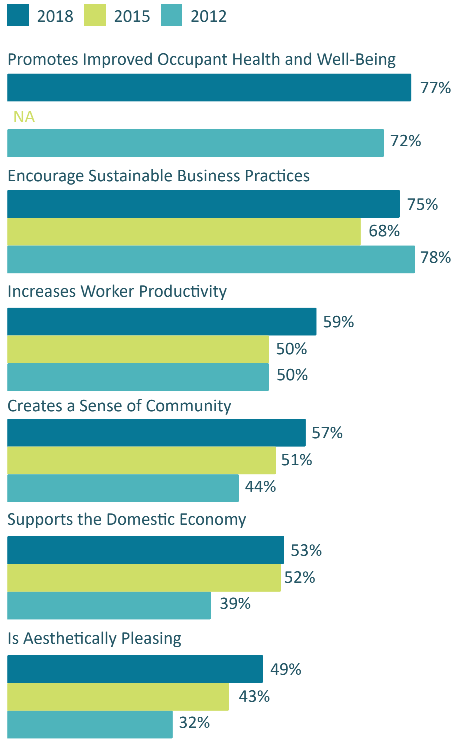


Figure 12 Social reasons for Building Green (Dodge Data & Analytics 2018).

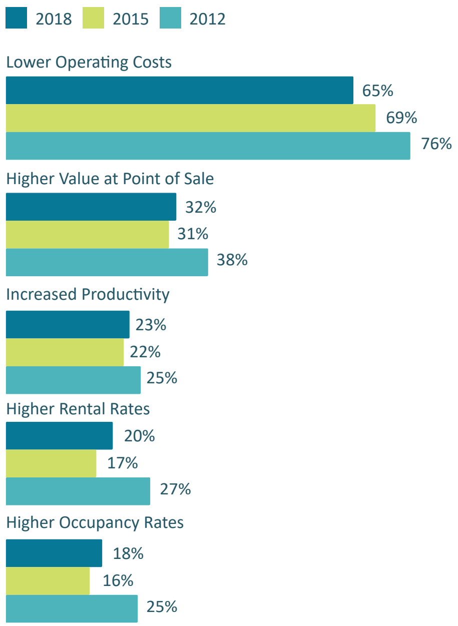


Figure 13 Economic reasons for Building Green (Dodge Data & Analytics, 2018).

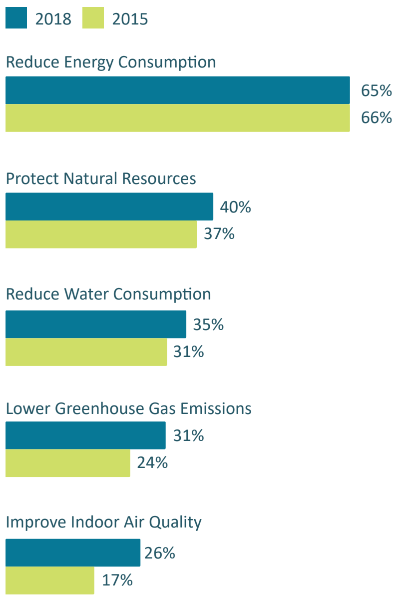


Figure 14 Environmental reasons for Building Green (Dodge Data & Analytics 2018).

The first certification system, called BREEAM, was developed in 1990 in England, and since then, many others have been developed over the years. According to a 2006 study, there have been more than 34 rating systems for green building or environmental rating tools available on the market, and the number has still grown[49]. If we now also look at product certifications, it is estimated that there are almost 600 certifications worldwide, and the number will continue to grow in the coming years[50]. Figure 15 shows the central systems worldwide and the number of countries in which they are used.

49 Fowler, K., Rauch, E., 2006. Sustainable Building Rating Systems Summary. Contract 2006. https://doi.org/10.2172/926974
50 Mohamed, M., 2019. Green Building Rating Systems as Sustainability Assessment Tools: Case Study Analysis. Sustainability Assessment at the 21st century. https://doi.org/10.5772/intechopen.87135

All rating systems have four main parts in common[51]:

- the categories that form a specific set of items related to the environmental performance considered during the rating;
- a scoring system that makes it possible to measure performance by accumulating points or credits when certain levels are reached in the various aspects analysed;
- a weighting system that makes it possible to give a different relevance to each specific category within the overall scoring system;
- final output to show the results of the environmental performance obtained during the scoring phase.

The following pages will describe the main features of three scoring systems: BREEAM, LEED, and Level(s). The first, as already mentioned, was the starting point for all these systems and is still used today; the second is the most widely used system in the world[52]; and finally the last, still in testing phase, was introduced by the European Community in 2018 to provide a common system for the whole EU.

Among the other most widespread certifications worldwide we find (Figure 15):

- the WELL[53] developed by International WELL Building Institute;
- Excellence in Design for Greater Efficiencies (EDGE)[54] developed by International Finance Corporation (IFC), a member of the World Bank Group;
- Deutsche Gesellschaft fur Nachhaltiges Bauen (DNGB)[55] developed in Germany;
- Living Building Challange (LBC)[56] developed by the International Living Future Institute;
- Haute Qualite Environmentale (HQE)[57] settled in France;
- Green Mark (GM)[58] developed in Singapore.

51 Bernardi, E., Carlucci, S., Cornaro, C., Bohne, R.A., 2017. An Analysis of the Most Adopted Rating Systems for Assessing the Environmental Impact of Buildings. Sustainability 9, 1226. https://doi.org/10.3390/su9071226
52 Zhang, Y., Wang, H., Gao, W., Wang, F., Zhou, N., Kammen, D.M., Ying, X., 2019. A Survey of the Status and Challenges of Green Building Development in Various Countries. Sustainability 11, 5385. https://doi.org/10.3390/su11195385
53 More information available on www.wellcertified.com/certification/v2
54 Further information available on www.edgebuildings.com
55 More information available on www.dgnb.de/de/index.php
56 Further information available on https://living-future.org/lbc/
57 More information available on www.behqe.com
58 More information available on www.bca.gov.sg/GreenMark/green_mark_criteria.html

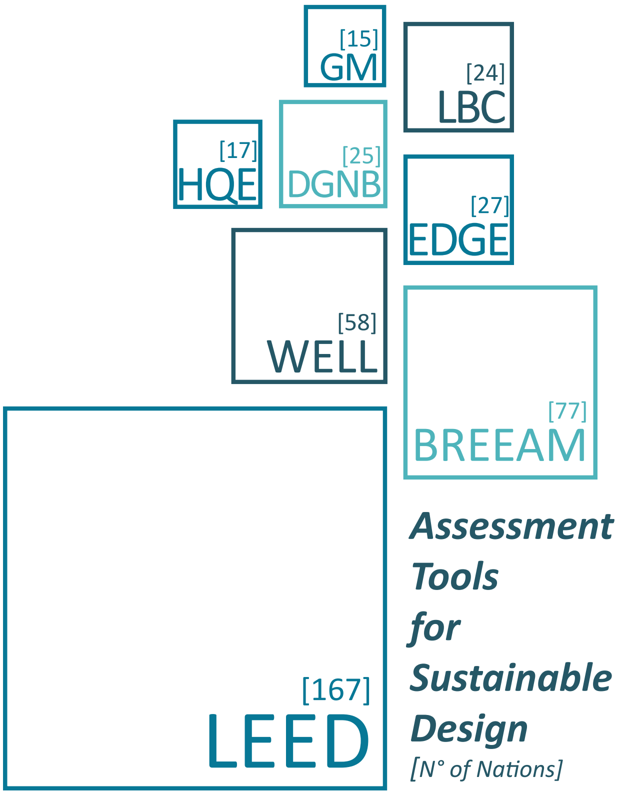


Figure 15 Top rating systems used and related number of countries in which each is applied (based on Zhang et al. 2019).

BREEAM The BREEAM system[59] (Building Research Establishment's Environmental Assessment Method) was developed in 1990 by BRE (Building Research Establishment), a world-leading multi-disciplinary building science organisation. The first of all scoring systems, it has been used as a basis for many of the certification systems. In England, it is the most widely used system and the achievement of BREEAM scores is required by several UK organisations, including English Partnerships, Office of Government Commerce, Department for Children Schools and Families, Housing Corporation, and Welsh Assembly.

Although BREEAM was initially available in two types, one for offices and one for housing, it is now available for a range of building types: offices, housing, industrial, multi-residential, prisons, shops, and schools. Besides, it is now not only limited to the UK but has taken off in 80 other countries and has more than 2 million registered projects and 565,000 certificates issued.

59 Further information available on www.breeam.com

The BREEAM system evaluates the performance of the buildings measured in nine categories (Figure 16) and gives it a score based on the values achieved. Each category is weighted to encourage projects to focus on the categories with the highest environmental impact and minimum standards are set to ensure that key aspects of performance across the standard are met to achieve the highest levels of certification. This provides a level of flexibility of use while maintaining the rigor of the standard.

Finally, the building is rated by a third party bodies based on the score obtained, which may be expressed by a minimum of 1 to a maximum of 5 stars, specifically: 1 star - Pass, 2 stars - Good, 3 stars - Very Good, 4 stars - Excellent and 5 stars - Outstanding. Based on this, the certificate assigned to the project is issued.

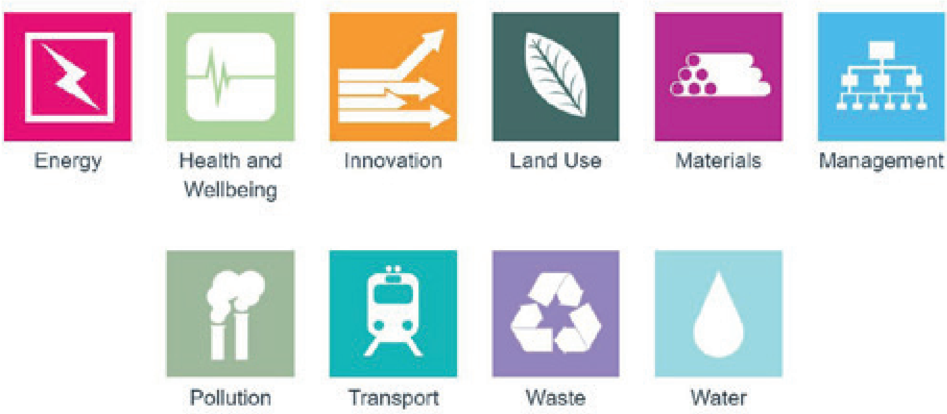


Figure 16 Categories of the BREAAM Rating system (www.breeam.com).

LEED The second system in chronological order is LEED (Leadership in Energy and Environmental Design), introduced by the U.S. Green Building Council (USGBC)[60] and in use since 2000 with its first version for new buildings (LEED-NC) in the United States of America. LEED is used throughout North America and in over 30 countries, with over 6,300 projects currently certified worldwide and over 21,000 registered projects. As of September 2010, it was used in more than 35 state governments, 380 cities and 58 counties have enacted sustainable laws, ordinances or policies, many of which specifically require LEED certification. Today it is used in 167 countries and has over 80,000 registered projects and about 32,500 certificates issued.

60 More information available on www.usgbc.org

One of the peculiarities of the LEED system is that it has been developed with an open process based on consensus, with the contribution of a wide range of building industry professionals and other experts, including the U.S. Department of Energy. Moreover, the need to evaluate the sustainability of a building is one of the reasons behind the LEED's definition. At the time of creation, some U.S. professionals found it difficult to decipher the claims of their competitors and building product manufacturers who had also started campaigns about how environmentally friendly their product or building was.

For each of the requirements that characterize the sustainability of a building, credits are assigned through a checklist. The level of certification obtained depends on the sum of the credits accumulated. Under the first version with the LEED-NC system, buildings were judged through a 69-point credit system in five environmental performance categories and an additional area for innovative strategies. Today the fourth version has been reached and the categories have increased (Figure 17), and there is no longer only the new building version. Today there are six variants of LEED, which in turn are further diversified for different uses or types of intervention, specifically are BD+C (Building Design and Construction), ID+C (Interior Design and Construction), O+M (Operations and Maintenance), Residential, Cities and Communities and Recertification.

Figure 17 Categories of the LEED rating system (www.usgbc.org).

Each category has one or more mandatory prerequisites, such as minimum energy and water use reduction, recycled waste collection and tobacco smoke control, and many requirements for specific sustainability strategies that score the building. If the credits obtained from the nine categories are added together, the final score and certification level are obtained from the four categories: Certificate, Silver, Gold, and Platinum (Figure 18).

Figure 18 Certification levels of the LEED rating system (www.usgbc.org).

The LEED certification process takes place through the LEED-Online website. It is based on four steps: project registration and rating system selection; the project team must then upload the documentation to demonstrate compliance with LEED requirements; the documentation is reviewed by the Green Building Certification Institute (GBCI); finally, LEED certification is obtained if all prerequisites and a sufficient number of credits are obtained.

Level(s) Level(s)[61] is a voluntary communication framework aimed at improving the sustainability of buildings developed by the European Commission in close cooperation with leading players in the sector, such as Skanska, Saint-Gobain, and Sustainable Building Alliance. Using existing standards, Level(s) provides an EU-wide approach to assessing environmental performance in the construction sector and helps to support the circular economy.

The Level(s) system was developed to provide a framework of common indicators across Europe to measure the sustainability performance of buildings. It is structured around six macro-objectives or categories for environmental impact throughout the life cycle of the building: greenhouse gas emissions, resource efficiency, water use, health and comfort, resilience and adaptation to climate change, and cost and value.

61 More information available on https://ec.europa.eu/environment/eussd/buildings.htm

The framework sets out three levels of performance assessment, to be achieved through the use of indicators (Figure 19):

- the common performance assessment involves using each indicator in the simplest and most accessible way, and aims to provide a common reference point for the assessment of building performance across Europe;
- the comparative performance assessment is aimed at professionals who want to make meaningful comparisons between functionally equivalent buildings;
- the optimized performance assessment involves the use of each indicator in the most advanced way.

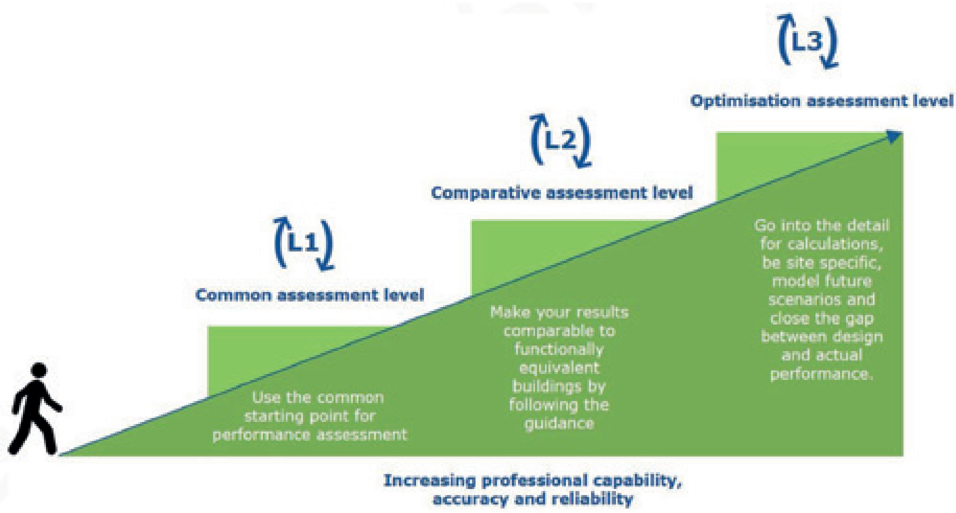


Figure 19 The three levels of performance assessment used in the Level(s) system (EU 2019).

The three levels are progressive in terms of the accuracy and reliability of performance assessment and the degree of professional skills and competencies required.

Before introducing the evaluation system on the market, the European Commision launched a two-year test phase in spring 2018. Investors, developers, designers, and manufacturers are testing Level(s) indicators in more than 130 different projects, 74 of which are residential, spread across 21 countries (Figure 20). The results obtained from this phase will be used to draft the final version of the Level(s) framework - to be launched around summer 2020.

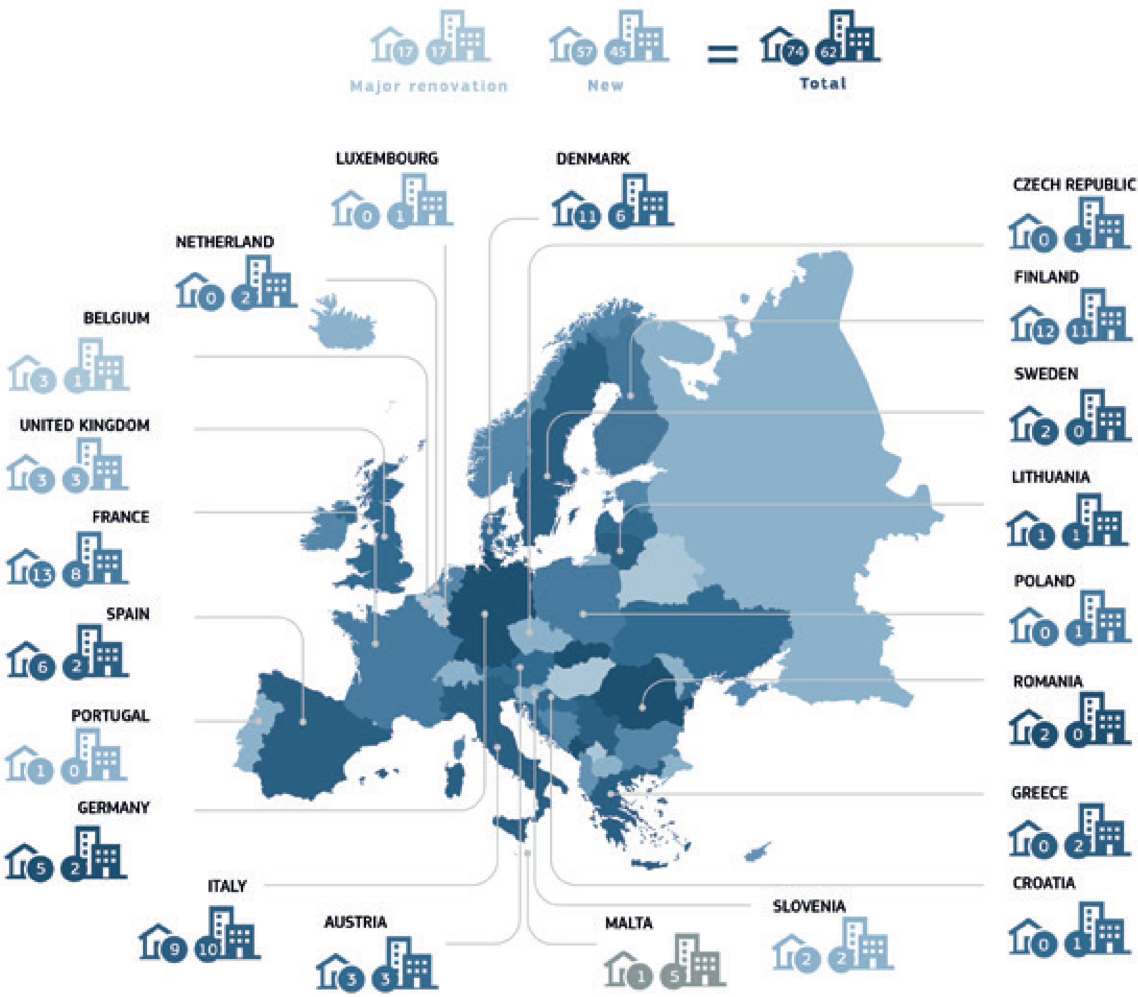


Figure 20 Overview of the testing phase of the Level(s) system (EU 2019).

2.3 Sustainable Design

The initial references for sustainable design date back to the 1960s. However, the principles behind them can be found much earlier in the still existing architecture and in the construction techniques, handed down from generation to generation and refined over time for the specific climatic characteristics of the site and the type of building materials available. Just think, for example, of the Eskimo igloos that are "a well-known solution to the problem of survival in extreme cold. These low hemispherical shelters deflect the winds and take advantage of the insulating value of the snow that surrounds them"[62]. Alternatively, to the constructions developed by the populations living in the opposite situation, in warm and arid climates, to protect themselves from excessive heat. These constructions are made with "massive adobe roofs and walls, which have good insulative value and the capacity to delay heat impacts for long hours, thus reducing the daily heat peaks. They also used very small windows. By packing buildings together, the amount of exposed surface was reduced"[63]. In hot and humid climates, on the other hand, the buildings were without walls to allow high ventilation and the roofs were large and covered with grass to create large areas of shade and isolate themselves from sunlight. These are just some of the many examples that could be given.

Over time these construction techniques have been forgotten and modified with the progressive introduction of new technologies and materials that have led to the prevalence of active techniques over passive ones. Over time, the building envelope has lost its function as a mediator between indoor and outdoor climate. Due to this inability of the building organism to determine conditions of well-being spontaneously, we are witnessing a worrying spread of summer air conditioning systems with increasing needs. This contrasts dramatically with the objectives of sustainable development, which focuses on reducing the environmental impact of buildings as a fundamental parameter of quality assessment. In order to address the issue of sustainability in resolutive terms, therefore, it is necessary to completely revise how a project is carried out, making all actions aimed at minimizing the need to use plant systems for the activation of suitable environmental conditions central[64].

Based on similar considerations, in the framework of the 1960s, a historical moment characterised by the energy crisis and the emergence of the principles that will lead

62 Olgyay, V., 1963. Design With Climate: Bioclimatic Approach to Architectural Regionalism, First Edition edition. ed. Princeton University Press.
63 Olgyay, V., 1963. *Ibid.*
64 Szokolay, S., 2008. Introduction to Architectural Science, 2 edition. ed. Routledge, Amsterdam; Boston; London.
65 Olgyay, V., 1963. *Ibid.*

Figure 21 Picture of the first prototype of a solar dwelling made by Felix Trombe and Jacques Michel in France (Wikimedia Commons/ofHouse).

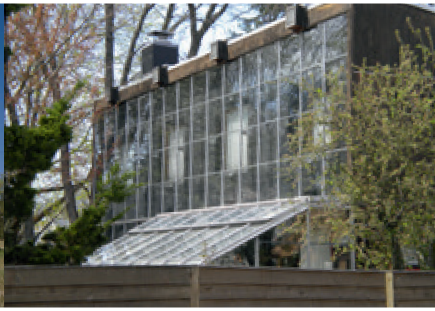


Figure 22 Kelbaugh House built in Princeton, New Jersey (www.centralnjmodern.wordpress.com).

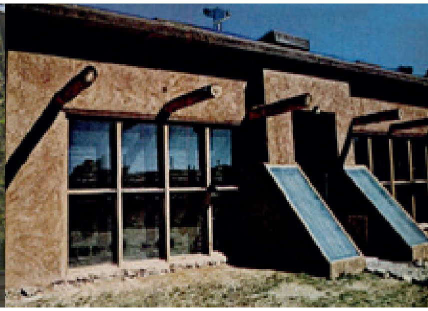


Figure 23 Historical image of one of the houses built in New Mexico with "The sundwellings project" (www.closedworlds.net).

to the definition of sustainable development, that the first manuals on sustainable design are to be found. Among them we find in 1963 "Design with Climate" by Olgyay[65], in 1969 "Man, Climate and Architecture" by Givoni[66] and "Design with nature" by McHarg[67].

In those years, there were also some significant experiments in the field of sustainable design. In the years 1962 to 1967, the first prototype of a solar dwelling[68] with the "Trombe wall" was built based on the work carried out in France by Felix Trombe and Jacques Michel in Odeillo, who were the first to experiment with the system previously patented by Edward Morse in 1881 (Figure 21). Similar to this example, there is the Kelbaugh Hous made in 1973 in Princeton, New Jersey[69] (Figure 22). The following year, the "The Sundwellings Project" in New Mexico was launched for the construction of solar houses adapted to the particular climatic conditions of the local area, commissioned by the Corners Regional Commission[70] (Figure 23).

From these early examples up to the present day, there have been many other experiences all united by the idea of constructing buildings capable of guaranteeing living comfort without the use of machines. "Suddenly a building was not performing

66 Givoni, B., 1969. Man, climate and architecture, Elsevier architectural science series. Elsevier, Amsterdam.
67 McHarg, I.L., 1969. Design with nature. Garden City N.Y. Published for the American Museum of Natural History [by] the Natural History Press.
68 Trombe, F., 1974. Maisons Solaires. Tech. Ing., 3, 1–5.
69 Kelbaugh, D., 1978. Kelbaugh house: Recent Performance. In: Proc. 2nd Passive Solar Conference. p. 69-75.

anymore, it was reduced to a mere container of space - a big blank Box, tube-fed by a whole arsenal of machines"[71]. The aim is to take a step back to improve the performance of the building and reduce its consumption, limiting the use of integrated active systems for air conditioning, heating, cooling, and mechanical ventilation and introducing the use of passive strategies (Figure 24). Achieving this objective would allow the construction sector to make a significant contribution to the global challenge for sustainable development, given the implications described in the previous paragraph.

The construction of sustainable buildings can be put into practice through the use of a series of measures and design criteria. These principles that the designer should adopt can be divided into three levels: environmental, typological, and detailed[72]. On the following pages, the three levels will be analysed individually and the essential criteria will be described for each one.

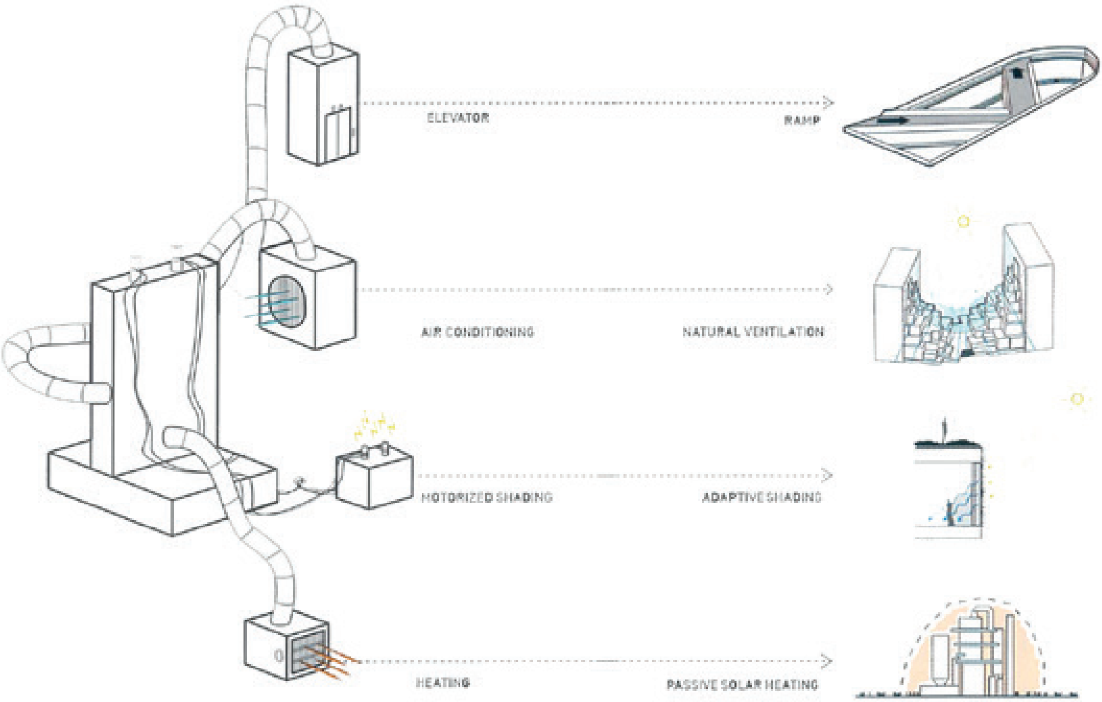


Figure 24 Schematic idea of substitution of active techniques with passive ones to achieve sustainable projects. (BIG 2015)

2.3.1 Environmental Level

The first step in the building analysis is to study and understand the context in which it is located. The external environment, with its specific factors for each site, can affect the internal living comfort, determining favourable conditions that can be exploited or negative ones that must be contrasted.

Environmental factors can be further divided into three groups.

Climate and Weather Conditions

The characteristics of the local climate and the resulting weather phenomena must be studied by collecting quantitative data on external environmental conditions (temperature, humidity, light, etc.). They make it possible to determine the consequent interactions between the outside and the building (heat flow, airflow, brightness, etc.) and identify the most suitable and optimal design choices.

The climate depends on the geographical region and different classifications have been identified over time. For example, one of the best known global classifications is the one made by Koppen in the first half of the twentieth century based on temperature, rainfall, and vegetation values; another is the one indicated by Olgyay defined concerning the hygrothermal well-being of human beings and which divides the planet into four climate zones[73]. Reducing the scale, we then meet further subdivisions, for example, in the case of the Italian peninsula, six climate zones are indicated obased on Day Degrees[74].

Data on climate and meteorological phenomena can be obtained primarily from national standards, which contain statistical data useful for a general indication of the climatic characteristics of the area analysed. However, a more in-depth study requires the use of more precise data that can be collected through local meteorological stations nearby or, if possible, installed in situ.

The quantitative data that can be used are listed below:

- climate zone;
- day degrees;
- outdoor temperatures;

70 A federally funded agency administered by the governors of New Mexico, Arizona, Colorado, and Utah.
71 BIG, 2015. Hot to cold. An odyssey of architectural adaptation: VA, 01 edizione. ed. Taschen, Köln.
72 Dassori, E., Morbiducci, R., 2011. Costruire l’architettura. Tecniche Nuove, Milano.
73 Olgyay, V., 1963. *Ibid.*

- relative humidity;
- wind speed and direction;
- rainfall;
- pressure;
- average horizontal irradiance (in the month of maximum irradiation);
- solar radiation in different orientations;
- daily hours of daylight and twilight;
- state of the sky;
- other additional data specific to the individual study.

Site Morphology The term "site morphology" indicates the study of the different "forms" of the analysed site. As in the previous case, also for morphology, some general statistical data are useful to have a first idea of the characteristics of the analysed area, while specific morphological statistical data can be used for detailed design considerations.

The data that can be collected are:

- geographical coordinates (latitude, longitude);
- height above sea level;
- maps of terrain altimetry;
- slope orientation;
- other additional data specific to the individual study.

Local Characteristics of the Site The last category of information that can be assessed at the environmental level are the local characteristics of the site that can affect the microclimate. This includes the following information

- soil type (characteristics of reflected sunlight, albedo, etc.);
- characteristics of vegetation;
- presence of water basins;
- presence of shading elements;
- proximity to large industrial or urban areas;
- other additional data specific to the individual study.

2.3.2 Typological Level

The analysis of the relationship between the external environment and the building, located in a specific place, is the main objective of the typological level. In particular, the typological criteria are used to generate design indications on the analysis of the volumetric and external characteristics of the building. The evaluation of the orientation of the construction, the shape of the building and the internal spaces organization are the three main typological criteria .

The orientation of the Construction The assessment of building orientation can be made concerning to three different environmental factors: solar radiation, wind regime, and site morphology.

Passive solar inputs in winter, summer, and intermediate regimes, when the outside temperature is between the winter and summer limits, are what influence when orientation is chosen based on solar radiation.

The choice of orientation concerning the wind regime, in order to use it in summer for natural ventilation or to shelter from it in winter, is made by using the environmental data collected on the direction and speed of the winds in the previous phase.

Finally, the assessment of the orientation according to the morphological characteristics of the site is made using the information on local characteristics.

The final aim of all three evaluations is to determine and optimize the orientation of the building elevations, the percentages and position of the transparent elements of the envelope, and the distribution of the interior spaces.

The shape of the Building In the history of sustainable design, several studies conducted on the optimization of the shape and volume of a building related to the factors of different climate zones can be found. These factors mainly concern: the shape, the S/V[75] compactness ratio of the building, and the internal distribution of space considering the specific properties of the site.

The climate primarily influences the shape of the building. For example, in hot and dry climates, compact shapes are optimal, with flat roofs and shaded open internal spaces; in hot and humid areas, elongated shapes with short east-west sides are pre-

74 Day Degrees are calculated as the sum of the differences between a conventional indoor temperature (20 °C) and the average daily outdoor temperature.

ferred for greater protection from more horizontal sun rays during the first and last hours of the day; in cold areas, compact shapes with sloping roofs are used; finally, in temperate areas, compromise solutions among those listed above are used[76].

The S/V ratio indicates the compactness of the building, which can again be used to determine the optimal shape regarding the climatic conditions of the site. It is also a value used in Italian legislation to prescribe specific requirements on the final energy performance of the building.

Inside the building, there are spaces used for different purposes and at different times of the day. Their distribution and organization can be established based on the information collected in the previous environmental level. For example, the service rooms (bathrooms, storerooms, stairwells, etc.) are located to the north in cold and temperate climate zones because they do not require particular radiation while they are located to the east and west in the hot zones to act as a filter and protection.

2.3.3 Detail Level

The detail level collects all the design principles and criteria concerning the choices of the technical and technological characteristics of the entire building system. These characteristics include the materials, construction elements and construction techniques to be used to achieve the expected result.

The choice of the most suitable materials and construction elements can be made considering their sustainability throughout the entire life cycle, from the extraction of raw materials to the demolition or reuse or recycling phase. The demand for more information on the environmental performance of products has been driven by the creation of certification and product labeling systems that are widely used today, such as the EPD[77] or Ecolabel certificate[78].

The construction techniques to be used can be chosen between active or passive ones. The first ones, as the term suggests, provide solutions that use active and energy-consuming systems. Passive techniques, on the other hand, are aimed at exploiting the free resources of the natural environment in order to guarantee living conditions of well-being inside the building. The principles underlying sustainable design aim to increase the use of passive techniques in order to limit the need to use active techniques accordingly.

75 The S/V ratio is calculated on the heat loss area (S) and the volume of the construction (V).
76 Olgyay, V., 1963. *Ibid.*
77 Further information available on www.environdec.com
78 More information available on https://ec.europa.eu/environment/ecolabel/

Passive techniques can be grouped for four different purposes:

- winter conditioning techniques: thermal insulation by reflection, resistance or capacitance; direct gain systems; semi-direct air-termination systems; indirect air-termination systems, independent air-termination systems and storage systems;
- techniques for summer air conditioning: sun protection systems; ventilation and air treatment systems;
- techniques for natural lighting: exploitation of daylight; exploitation of diffused light; conveyed light;
- techniques for noise control: sound barrier, sound insulation, sound absorption.

3 DIGITIZATION

Digitization and extraordinary technological advances are changing our society by reducing the gap between the digital and physical worlds. This radical transformation is identified as the fourth industrial revolution. Compared to the previous three, it is transforming every area of human activity very quickly and with a more significant impact. The fourth industrial revolution is based, for example, on the connection between physical and digital systems, on complex analysis through Big Data, and the use of intelligent machines interconnected and connected to the Internet in all components, products and production equipment.

The construction industry, although lagging behind other sectors, is facing the challenge of entering the age of digitisation, with the quick alignment of production, construction, and management processes to the fundamental concepts of industry 4.0. Several new technologies are already available in the Construction 4.0 panorama and applicable to all phases of the construction process, such as augmented reality, drones, 3D scanning and printing, Building Information Modelling (BIM), autonomous machines, and equipment, and advanced building materials. Among them will be BIM defined as a software platform common to all stakeholders in the construction process that will allow us to use virtual modeling and to collect all the information necessary to design and manage any aspect of the built life.

This chapter will focus on digitization. Section **3.1** will outline the principles behind the Fourth Industrial Revolution and present an overview of current initiatives at the global and European levels. The digital transformation in the construction sector will be discussed in section **3.2**. Finally, paragraph **3.3** will deal with Building Information Modeling, its main features will be described, and the current regulatory framework will be presented, with an in-depth analysis of the Italian context.

3.1 The 4th Industrial Revolution

"It's just mind-boggling what has been achieved in the past 10 years. The speed by which things are changing its increasing at astonishing rates, product cycles are much shorter, innovation is happening faster, and it's very challenging for the c-suite, as well as employees, to keep up with the pace. We have pivoted from a product-oriented organization to a service-oriented organization, which requires different people, different skill sets, and, at times, painful transitions."

Harold Goddijn, CEO of TomTom NV

The radical change in society that we are experiencing, due to extraordinary technological advances, is opening a new chapter in human development. The many technological innovations that are emerging, and will probably continue to do in the coming years, have integrated and generated significant changes both in our daily routine and in all aspects of society and industry. This change is identified as the fourth industrial revolution. An era when the gap between the digital world and the physical one is being reduced, and they will be completed integrated.

The evolution of our society that has led to this further change is the result of a long journey over the last two centuries. In it, we can recognize some changes or moments of passage that are remembered as "industrial revolutions". Before the one we are going through now, as its name suggests, there were three other revolutions.

The first industrial revolution began around the 18th century. It was characterized by the invention of the steam engine and loom weaving, the mechanization of production, and the use of machines driven by mechanical energy. These helped to increase productivity and reduce production costs, which in turn led to an increase in living standards and the growth of cities around factories. Steam engines also allowed the development of printing and railways, so people and information could move faster than ever before[1].

The second industrial revolution was generated at the end of the 19th century with the advent of mass production. By introducing the assembly line, which could be powered by electricity produced from oil and gas, it was possible to improve the efficiency of industrial production further.

1 UNIDO, 2017. Accelerating clean energy through Industry 4.0: manufacturing the next revolution. Nagasawa, T., Pillay, C., Beier, G., Fritzsche, K., Pougel, F., Takama, T., The, K., Bobashev, I.
2 Mrugalska, B., Wyrwicka, M.K., 2017. Towards Lean Production in Industry 4.0. Procedia Engineering, 7th International Conference on Engineering, Project, and Production Management 182, 466–473. https://doi.org/10.1016/j.proeng.2017.03.135
3 Schwab, K., 2017. The Fourth Industrial Revolution. Currency, New York.

The third revolution, also known as the digital revolution, is characterized by the introduction of electronics in the 1970s. It opened up new opportunities for automation and engineering, enabling new technological advances and a further increase in productivity.

The fourth revolution that we are experiencing today can transform every industry much faster and with a more significant impact than any of the previous three[2]. It is based on the connection between physical and digital systems, complex analysis through Big Data, and the use of intelligent machinery interconnected and connected to the internet in all components, products, and production equipment. “Digital technologies that have computer hardware, software and networks at their core are not new, but in a break with the third industrial revolution, they are becoming more sophisticated and integrated and are, as a result, transforming societies and the global economy”[3]. Industries are transforming and moving towards a “smarter” configuration in which the traditional demand for physical space is replaced by that of digital space and virtual systems.

Another of the main peculiarities of this fourth revolution is disruptive speed. Emerging technologies and innovations are spreading much faster and on a larger scale than previous revolutions. “The spindle (the hallmark of the first industrial revolution) took almost 120 years to spread outside of Europe. By contrast, the internet permeated across the globe in less than a decade”[4].

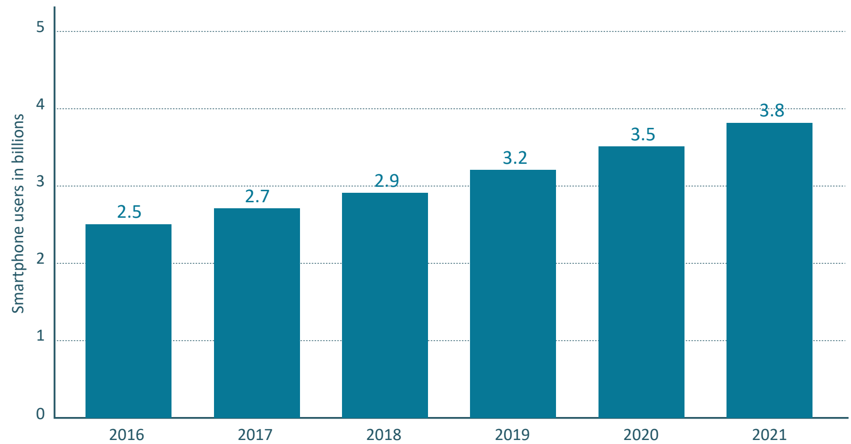


Figure 25 Number of smartphone users worldwide from 2016 to 2021 (www.statista.com).

4 Schwab, K., 2017. *Ibid.*

An example of this unprecedented speed is the number of smartphones in circulation. Since the beginning of the fourth industrial revolution, set in 2007 with the launch of the first smartphone on the market, just over ten years later, it is estimated that 3.2 billion smartphones will be used in 2019[5] (Figure 25).

Another highlight of this transformation is the presentation in 2011 of the "Industry 4.0" concept at the "Hannover Mess"[6] event by the three representatives of the German Federal Government's Scientific and Economic Research Union. Since then, "Industry 4.0" has become a widely used definition when talking about the advent of this brand new industrial revolution, thanks to computer-physical systems, the Internet of Things (IoT), the Smart Factory and the new generation of production systems able to exchange information autonomously through Machine to Machine (M2M) communication modes.

The development of this future scenario is guided by the four key concepts of Industry 4.0 (Figure 26). Specifically:

- **Digital data, their collection and analysis**
  Industry 4.0 digitizes and integrates processes vertically throughout the organization, from product development and purchasing to production, logistics, and service. All data related to operational processes, process efficiency, and quality management, as well as operations planning, are available in real-time, supported by augmented reality and optimized in an integrated network. The availability of this massive amount of data, also collected with the help of smartphones, social network sensors, is an opportunity for advanced industries to develop and refine integrated solutions and products to meet the growing needs of end customers.
- **Automation**
  The possibility to use new technologies for the development of autonomous and self-organizing systems opens new scenarios and communication channels between man-machine and machine-machine.
- **Connectivity**
  Industry 4.0 explores new possibilities of connection and synchronization of activities and phases that until now have been distinct, thanks to new languages and channels of wireless and non-wireless communication.

5 Statista, 2019. Number of smartphone users worldwide from 2016 to 2021 (in billions), https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/

6 Hannover Mess is the most important international platform a hot spot for industrial transformation. It takes place every year in the spring in the exhibition centre of the German city of Hannover. Further information on www.hannovermesse.de

- **Digital access**
  Access to the Internet and internal networks is the basis and the necessary condition for the implementation of the previous key concepts. It allows opening up new channels of communication and access to information and collected data. Statistics show that in 2019 58.8% of the world's population has full access to the network[7].

In addition to these fundamental concepts, there are several technologies, also called enabling technologies[8], that have been revolutionizing the entire industry in recent years. The nine key technologies[9] are:

- **Autonomous robots**
  Manufacturing industries have long used robots to tackle complex assignments. Robots are evolving to achieve even greater utility, becoming more autonomous, flexible, and cooperative. Eventually, robots will interact with each other, work safely side by side with humans, and learn from them. These robots will cost less and have a more exstensive range of capabilities than those used in production today.
- **Simulations**
  Simulations will be used more widely in facility management to leverage real-time data and reflect the physical world in a virtual model, which can include machines, products, and humans. This will allow operators to test and optimize machine settings for the next online product in the virtual world before the physical step, reducing machine setup time and increasing quality.
- **Integrated Systems**
  With Industry 4.0, companies, departments, functions, and capabilities will become much more consistent as inter-company and universal data-integration networks evolve and enable truly automated value chains. System integration will be both vertical, across the entire supply chain from product development to logistics, and horizontal, extending beyond internal operations to customers and all partner entities.

7 World Internet Users and 2019 Population Stats. https://www.internetworldstats.com/stats.html
8 Gerbert, P., Castagnino, S., Rothballer, C., Renz, A., Filitz, R., 2016. Digital in engineering and Construction. The Boston Consulting Group.
9 Probst, L., Lefebvre, V., Martinez-Diaz, C., Bohn, N. U., PwC, Klitou, D., Conrads, J., CARSA, 2018. Digital Transformation Scoreboard 2018. EU businesses go digital: Opportunities, outcomes and uptake. Luxembourg: Publications Office of the European Union. https://goi.org/10.2826/821639

- **Internet of Things (IoT)**
  Industry 4.0 means that more devices, sometimes including unfinished products, will be enriched with integrated processing. This will allow communication between the elements of production, not only inside the company but also outside. The devices will be able to communicate and interact with each other and with more centralized controllers if necessary. This will also allow for the decentralisation of analysis and decision making, enabling real-time responses.
- **Cybersecurity**
  The increase in interconnections and the use of standard communication protocols provided with Industry 4.0, lead to a consequent need to protect industrial systems and production lines from threats. The attention to the computer security of the systems has increased considerably and secure and reliable communication routes have been developed, as well as sophisticated identity and access management of machines and users.
- **Cloud Computing**
  The increased sharing of data across sites and business boundaries and the use of increasingly efficient cloud technologies that reach reaction times of just a few milliseconds will require the use of data and functionality in the cloud. It will enable more data-based services enhanced by cloud functionality, such as online information storage, cloud computing, and external data analysis services.
- **Additive production**
  Additive production systems, such as 3D printing, will increase the efficiency of material use and increase the possibilities for customization. Companies have just started to adopt additive manufacturing, and for now, it is only used for prototyping and producing individual components. However, with Industry 4.0, these additive production methods will spread and be used to produce small batches of custom products.
- **Augmented reality**
  Augmented reality-based systems support a variety of services, such as selecting parts in a warehouse, sending repair instructions on mobile devices, or displaying different design solutions in real-time. These systems are current-

10 Probst et al. 2018. *Ibid.*
11 The target audience for the survey was companies in the food and construction sectors across the 28 EU Member States. The online questionnaire was distributed by e-mail to approx. 16,000 companies using the online survey tool InterviewTM in 2017. A total of 120 responses from C-level executives were collected and used for the analysis.

ly in their infancy, but in the future, companies will make much higher use of augmented reality to provide workers and customers with real-time information to improve working procedures and decision-making.

- **Big Data**
  Within Industry 4.0, the complete collection and evaluation of data from many different sources, such as equipment, management systems, or customers themselves, will become the standard for predicting and supporting real-time decision making.

The European report on digital transformation published in 2018[10] and developed through the analysis of data obtained from an online questionnaire[11], shows some impressive results on the adoption of crucial technologies for transformation. In addition to established and mature technologies, new technologies related to industry 4.0 show a high level of adoption by the companies surveyed. In particular, the most widespread are big data and data analytics, the cloud, and the Internet of things as they are adopted by at least 20% of the companies in the sample while the least widespread is 3D printing with a level of adoption by the industries that answered the questionnaire of only about 5%.

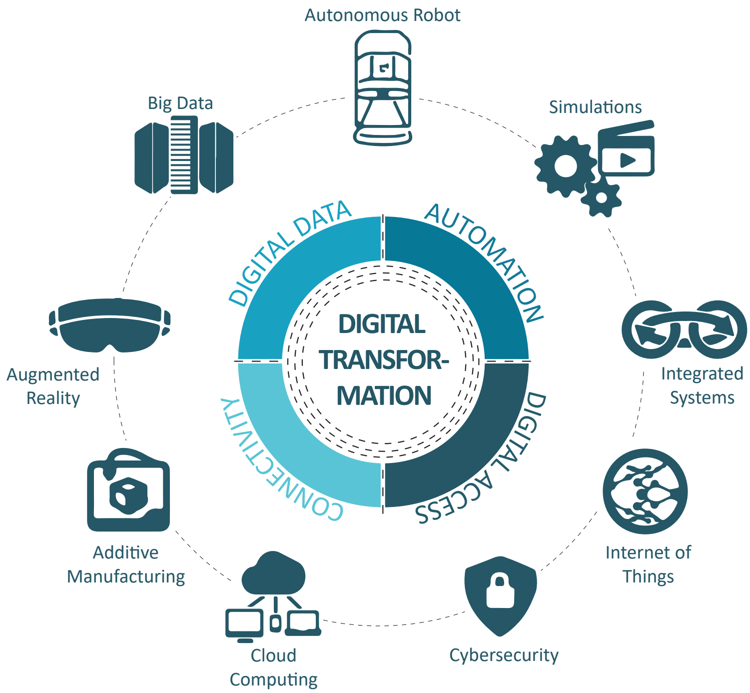


Figure 26 Industry 4.0: fundamental concepts and digital technologies.

A further in-depth analysis, proposed by the same report, concerns the differences in the take-up of new technologies to the characteristics of the companies studied. Three significant differences were identified in terms of size, age of the company, and level of development.

About enterprise size, the survey shows that smaller enterprises are more likely to adopt digital technologies than larger enterprises. Almost 75% of small enterprises, less than ten employees, say they have adopted at least one digital technology for business purposes, while this share decreases for larger enterprises. 68% of enterprises with 10 to 50 employees, 58% of enterprises with 50 to 240 employees, and 50% of large enterprises - with more than 250 employees - report having adopted digital technology for business purposes (Figure 27).

By dividing companies into five different age groups (<2 years, 3-5 years, 6-10 years, 10-15 years, >15 years), the report shows that young (3-5 years) and middle-aged (10-15 years) companies have the highest degree of technology adoption among the sample. On the other hand, companies aged 6-10 and over 15 have the lowest adoption rate, around 60%. However, it can be said that this result is not so significant as companies under 6 can be considered as already born in the digital age (Figure 28).

Finally, an assessment of technology adoption by the development phase reveals that all start-ups and developing companies have the highest share of adoption, over 78%, while companies developed on the national market have the lowest share (47%) (Figure 29). This is not surprising as most start-ups are digital technology-oriented from the outset and are more dynamic and open to the international market.

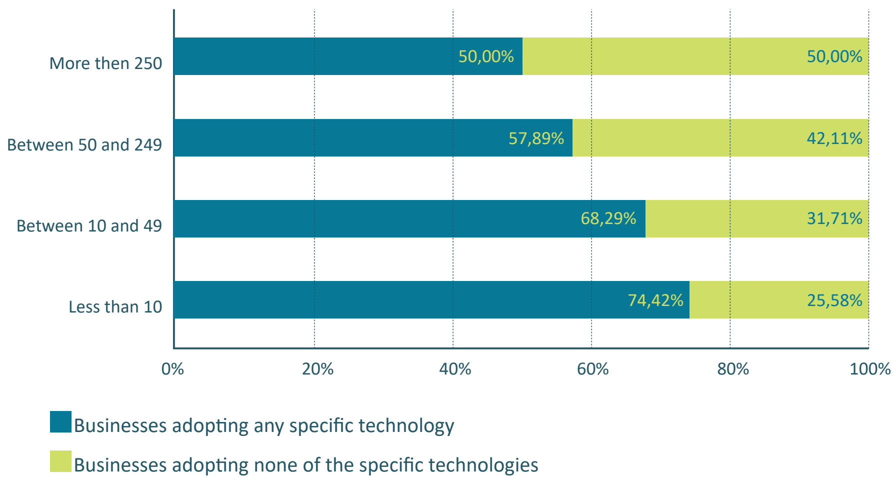


Figure 27 Adoption of technological innovations based on the size of the company (Probst et al. 2018).

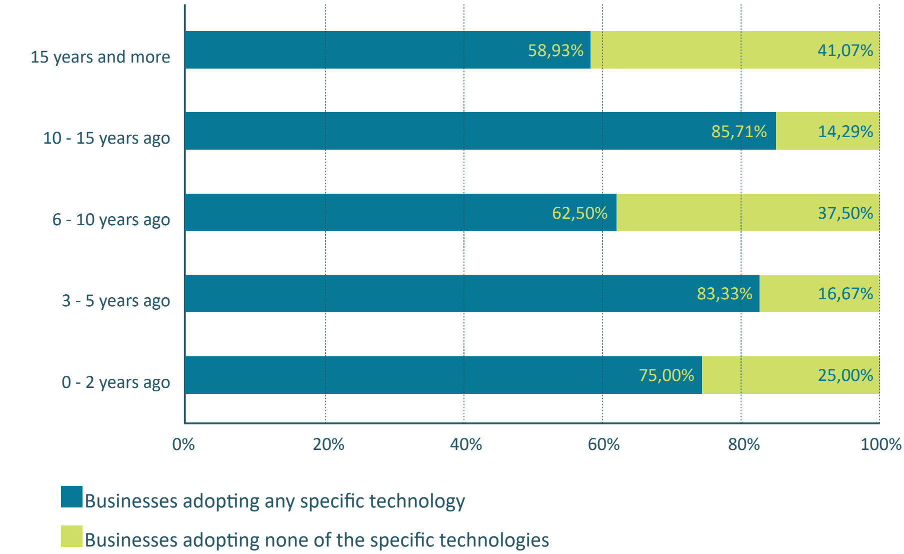


Figure 28 Adoption of technological innovations based on the age of the company (Probst et al. 2018).

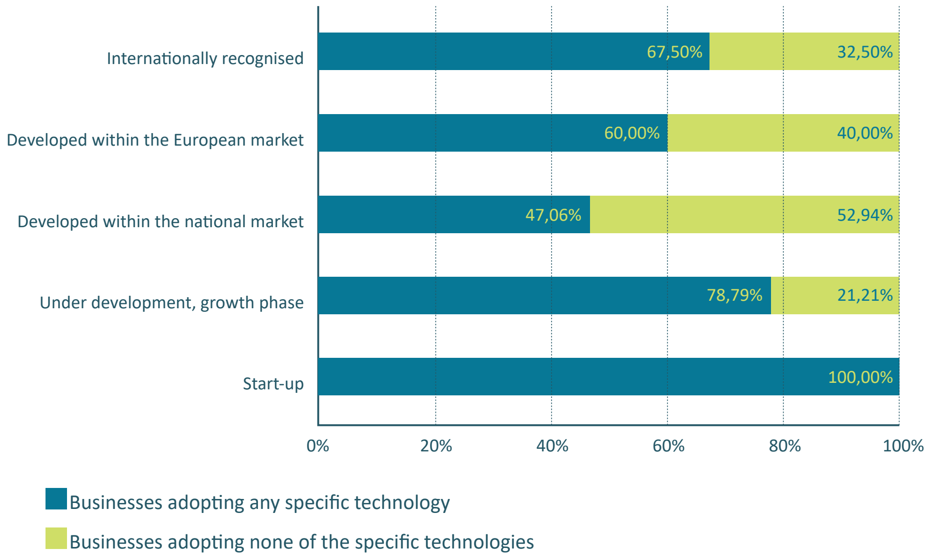


Figure 29 Adoption of technological innovations based on the development stage (Probst et al. 2018).

3.1.1 Industry 4.0 Initiatives

Driven by the key concepts described above and linked to information exchange and integrated control of products and machines acting simultaneously in an intelligent and interoperable way[12], digital transformation will lead to new, more efficient, and less expensive production systems. The profound connotation of this transformation has already been described, and it is therefore clear that, although it is taking place at unprecedented speed, it also requires significant efforts. Since 2011 with the introduction of industry 4.0, researchers and companies have embarked on this path through significant investments in terms of economic and human resources.

Investments have been estimated at around $907 billion over the next five years. They will lead to about $493 billion in additional revenue per year, as well as substantial efficiency gains and cost reductions, as demonstrated by the 2016 Global Industry 4.0 Survey[13]. Investment levels will be higher in the electronics sector, at around $243 billion, and in second place in the engineering and construction sector, at around $195 billion (Figure 30). Looking to the future, many of those who have not already invested, plan to do it soon. The advanced implementation of Industry 4.0 will become a qualifying element for competitions and tenders and is also likely to be seen by investors as a qualifying element in their choice of financing. Companies that have not kept pace will not only struggle to maintain market share but will also likely face higher capital financing costs.

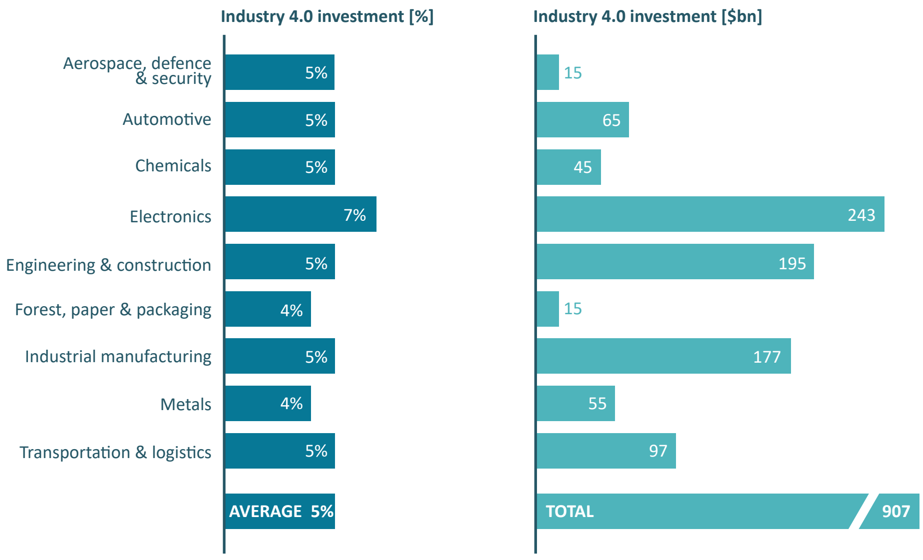


Figure 30 Companies in every industry sector are planning massive investments (Geissbauer et al. 2016).

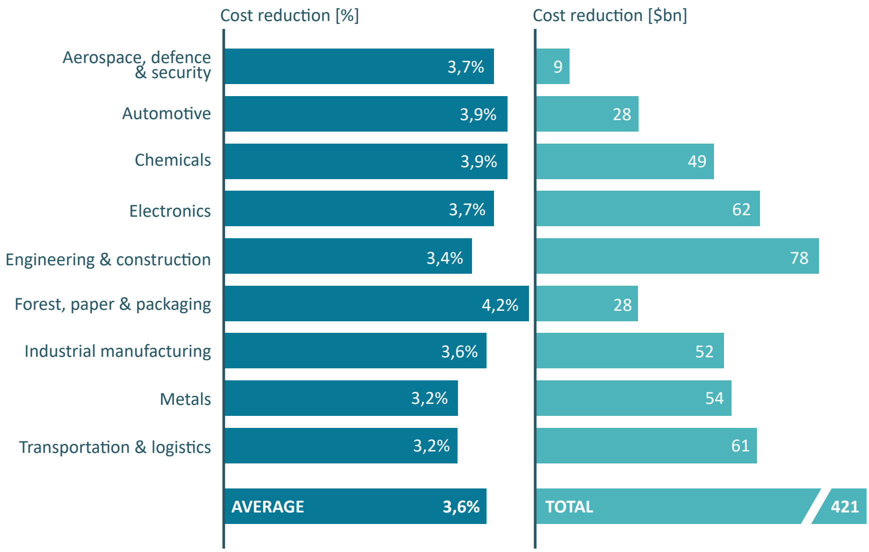


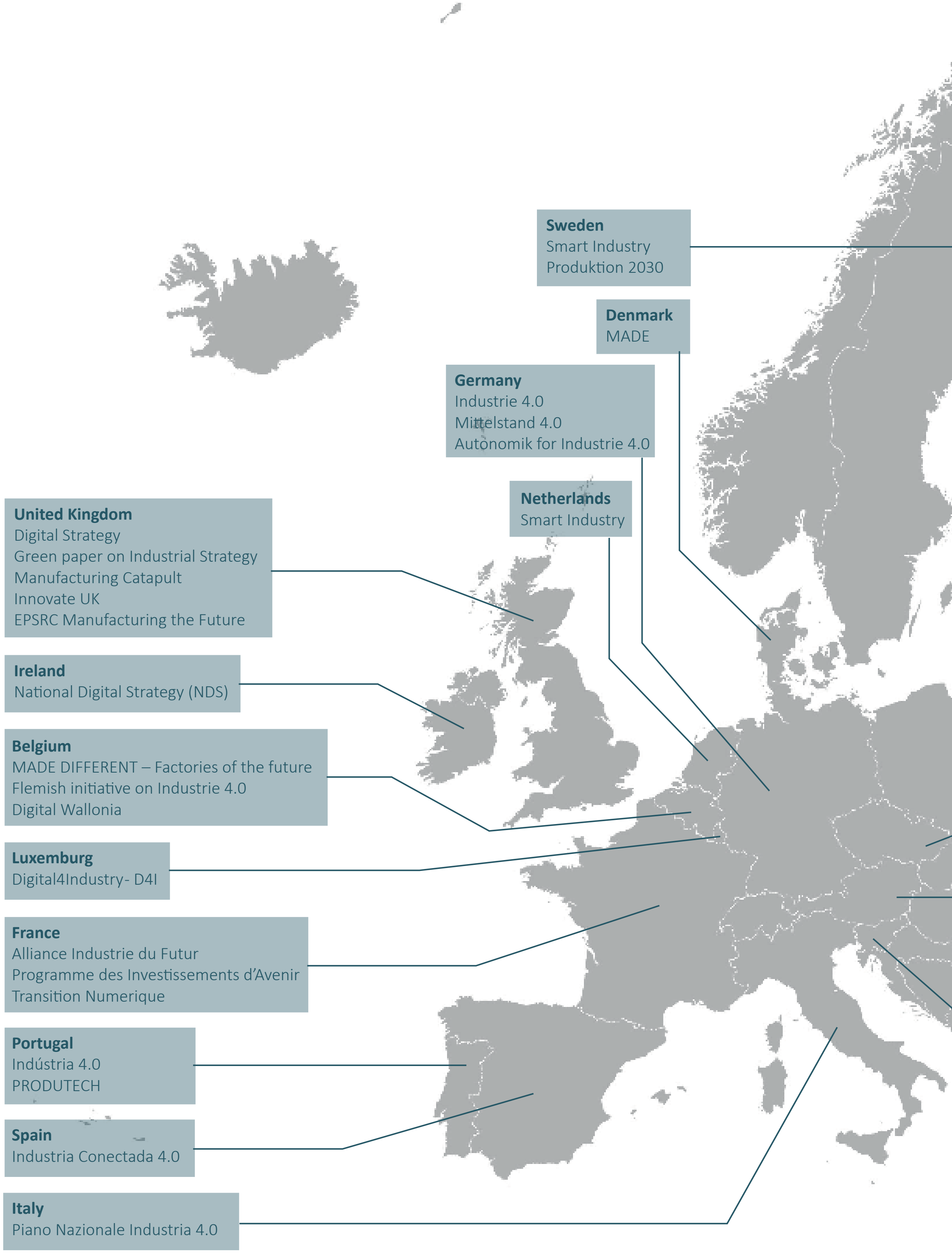
Figure 31 Companies in every industry sector expect a significant reduction in cost (Geissbauer et al. 2016).

Companies expect that these investments, in terms of digital evolution, will lead to a substantial cost reduction, on average 3.6%, corresponding to an annual efficiency increase of 4.1%. High levels of cost reduction are expected in every industry sector, but the highest monetary value is in engineering and construction, with $78 billion (Figure 31).

In addition to this framework represented by the investments that individual companies plan to use for their internal innovation/transformation, there are several national plans to support the development of industry 4.0. Since 2011, the number of national and regional initiatives supporting the transformation process towards smart production has increased significantly.

In 2011, the U.S. government launched the Advanced Manufacturing Partnership to renew the country's manufacturing industry and return it to its central position in terms of employment capacity. In 2012, the National Strategic Plan for Advanced

12 Qin, J., Liu, Y., Grosvenor, R., 2016. A Categorical Framework of Manufacturing for Industry 4.0 and Beyond. Procedia CIRP, The Sixth International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV2016) 52, 173–178. https://doi.org/10.1016/j.procir.2016.08.005
13 The document is the final report of a study on industry 4.0 with more than 2000 participants of the nine major industrial sectors and 26 countries. Geissbauer, R., Vedso, J., Schrauf, S., 2016. 2016 Global Industry 4.0 Survey. Industry 4.0. Building the digital enterprise. PwC.


Sweden
Smart Industry
Produktion 2030
Denmark
MADE
Germany
Industrie 4.0
Mittelstand 4.0
Autonomik for Industrie 4.0
Netherlands
Smart Industry
United Kingdom
Digital Strategy
Green paper on Industrial Strategy
Manufacturing Catapult
Innovate UK
EPSRC Manufacturing the Future
Ireland
National Digital Strategy (NDS)
Belgium
MADE DIFFERENT – Factories of the future
Flemish initiative on Industrie 4.0
Digital Wallonia
Luxemburg
Digital4Industry- D4I
France
Alliance Industrie du Futur
Programme des Investissements d'Avenir
Transition Numerique
Portugal
Indústria 4.0
PRODUTECH
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Industria Conectada 4.0
Italy
Piano Nazionale Industria 4.0

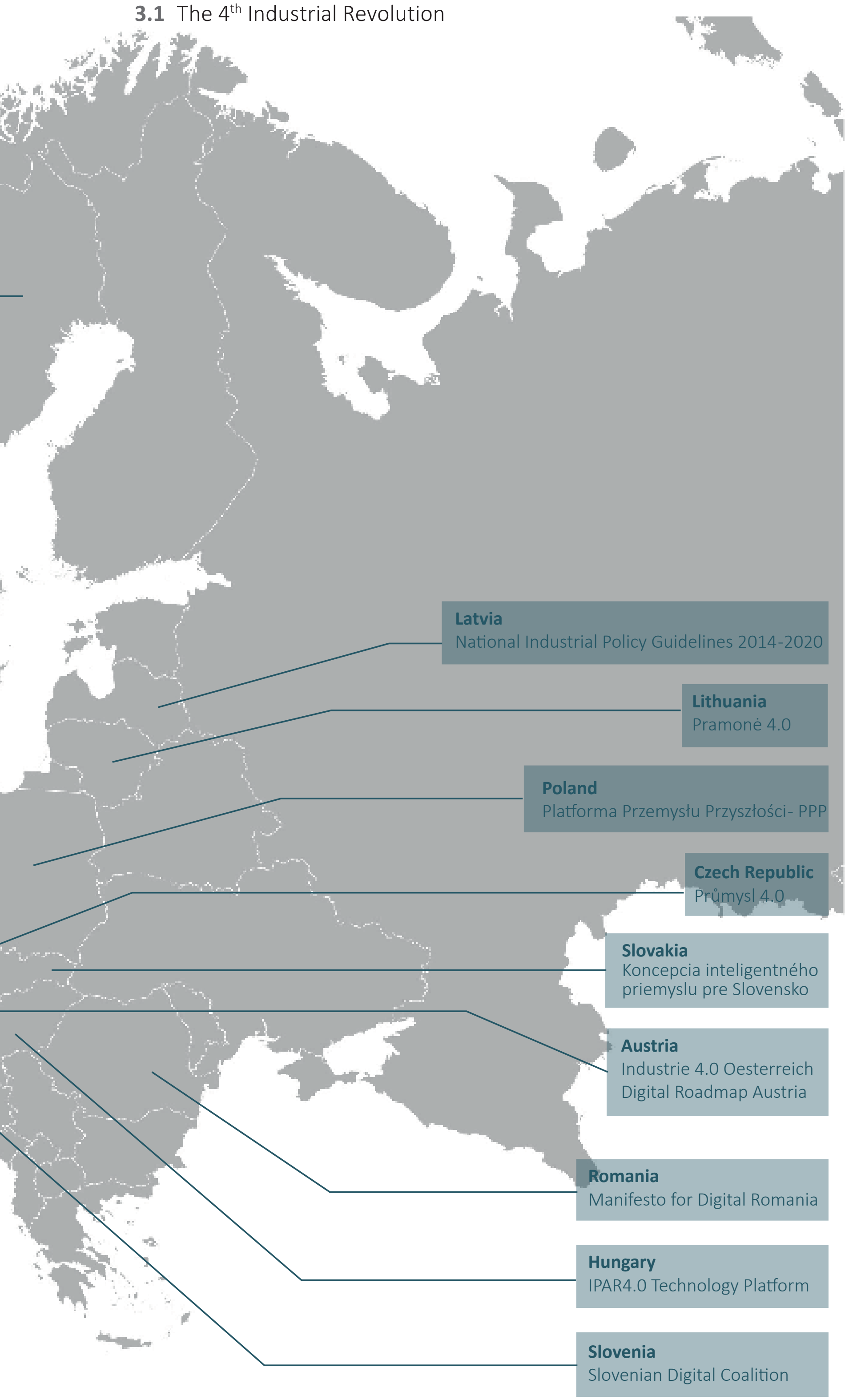


Figure 32
Maps of EU industry 4.0 initiatives registered on the EU platform.

Manufacturing was published, with substantial investment in research projects, institutes, and laboratories of excellence for the dissemination of technological expertise[14]. The "Industrial Internet Consortium", founded in 2014 in the United States, connects several organizations, not only Americans, interested in developing, applying, and testing the technologies needed to accelerate the growth of the Industrial Internet, identifying, bringing together and promoting best practices[15]. Many other countries offer similar initiatives such as the Chinese "Made in China 2025"[16] or the Japanese "Industrial Value-Chain Initiative"[17].

In the European context, there are more than 30 national and regional initiatives related to Industry 4.0, which are also supported and further linked by EU activities aimed at creating a European Digital Single Market. Since the first half of 2016, the European Commission, together with the Member States and industry, has established a governance framework to mobilise stakeholders, exchange best practices, and support the coordination of EU and national initiatives.

The European platform of national initiatives[18], launched in March 2017, is at the heart of the coordination effort. The platform plays a crucial role in the introduction of digitisation of the industry across Europe. Through the platforms, initiatives can be shared, collaboration and joint investment can be activated, an examination of common approaches to regulatory problems is possible, and the means for retraining the workforce are further exchanged. Several national or regional initiatives are registered on the platform (Figure 32).

3.1.2 Industry 4.0 Challenges

The transformation of industrial processes and the economy towards the principles of industry 4.0 is a path full of challenges. Companies have to face the most significant cultural and organizational disruptive transformation, knowing how to find the right technology and then buy it and adopt it. A cultural and organizational transformation requires long-term programs of change.

One of the first challenges directly concerns the States and the governmental bodies, which are called upon to create political frameworks suitable for this transformation and the new future scenario. Industry 4.0 and digitization are mainly driv-

14 UNIDO, 2017. *Ibid.*

15 The Industrial Internet Consortium 2017. "A Global not-for-profit Partnership of Industry, Government and Academia." https://www.iiconsortium.org/about-us.htm [Accessed: 17 Dec 2019]

16 More information available on http://english.www.gov.cn/2016special/madeinchina2025/

17 More information available on https://iv-i.org/wp/en/

18 https://ec.europa.eu/growth/tools-databases/dem/monitor/category/national-initiatives en by stakeholders and companies that often have a different pace and speed than politics and government. This different timing in creating regulations and frameworks could lead to their ineffectiveness if drafted and enacted too late. They are indispensable, as mentioned above, not only to support the transformation but also to prevent and control its potential adverse effects, such as privacy management, data security, working conditions, and the environment. Moreover, the race for innovation and the speed of technological development could bring a crucial advantage for pioneer countries or companies. In combination, the total absence of regulations or the presence of weak regulations would give the few top runners a significant influence, especially from an economic point of view.

Inequalities between the economic development of industrialised and developing countries could be further exacerbated if countries in the South fail to reap the benefits of digital development. The challenge to limit these possible global inequalities is therefore clearly evident. The aim will be to enable developing and least developed countries to use the possibilities offered by ICT and industry 4.0 to achieve their development priorities.

Data security and privacy are other pressing challenges for the future. Companies have digitized their processes and connected all devices and machines to the network, so the fear of being vulnerable and attacked by hackers is increasingly tangible. This also increases the need to protect critical industrial systems and production lines from cyber threats. As a result, the development and adoption of secure communications, as well as sophisticated machines for identity and user access management, are essential. The European Union has issued EU Regulation 2016/679[19], known as GDPR - General Data Protection Regulation, on the protection of individuals about the processing and free movement of personal data. It is a concrete response to the protection needs increasingly felt by EU citizens, due to technological developments and new models of economic growth.

In 2016, the German Mineral Resources Agency (DERA) published a study entitled "Raw materials for emerging technologies 2016"[20], which highlights a new challenge for the future related to raw materials used in industry 4.0. Each digital device is based on hardware that requires specific raw materials for its production. Due to

19 Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation).

20 Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. 2016. "Summary - Raw materials for emerging technologies 2016." DERA Rohstoffinformationen. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccn/2016/Zukunftstechnologien_Zusammenfassung_EN.pdf the increasing diffusion and application of digital technologies, the demand for raw materials will also increase, raising questions about their availability. In this document, DERA predicts that in 2035 the crucial materials for our society will probably be lithium and heavy rare earths[21].

Above all these challenges, although each one fundamental, there is an even more important one: the human being. Man is the centre of this disruptive transformation, and technologies are made to support and help humanity and not to replace it. It is necessary to consider the social impact of this transformation and how digitization can influence the relationship between man and machines and also the "future of work", i.e. the quality and quantity of jobs. An inherent conflict could, for example, arise in human-machine interaction: if humans were to follow the decisions of machines that they can no longer fully understand, this could probably lead to frustration. Therefore, humans must be an integral part of this transformation, understand its motivations and changes in industries and find their place to be part of it.

"Artificial intelligence will be able to drive cars better than the existing humans, and in the United States alone, that represents nearly 1.5 million jobs that could disappear if the technology were allowed to dominate. That's precisely why we need to make sure that we use this new wave of technology as a positive force for good. And that requires us to not just look at the short-term financial interest, but adopt a holistic approach to the technology."

Deloitte Insights 2019

21 Marscheider-Weidemann et al., 2016. *Ibid.*

3.2 Construction 4.0

"Digital construction is not an abstract concept at all, it's very tangible. We can use advanced technologies in construction to improve things like the air quality of a particular location or to ensure that traffic problems are lessened, or that the energy efficiency of buildings is maximised. These types of things can have a big impact on the health and wellbeing of people. Nations the world over will take note once they see the benefits."

Milena Feustel, co-chair of the digital construction focus group, EU BIM

Most industrial sectors have experienced disruptive changes and have reaped the benefits of industry 4.0 innovations, as shown in section 3.1. In this global transformation, the construction sector has also been involved, but "according to statistics, construction is the least digitized sector in the EU"[22].

The construction industry is the one that has been most hesitant to take full advantage of the latest technological opportunities, due to its peculiar historically reluctant and slower nature, compared to other sectors, in adopting and adapting to innovations. Thus, while most other industrial sectors can benefit from the positive consequences of this new situation - improved productivity, efficiency or sustainability - the overall productivity of the construction sector has stagnated and remained almost flat over the last 50 years (Figure 33). As John M. Beck, Executive Chairman of Aecon Group, says: "looking at construction projects today, I do not see much difference in the execution of the work in comparison to 50 years ago". Therefore, it is not a bold statement to say that our sector is the protagonist of "delayed innovations" compared to other fields of human activity: where others have been able to take advantage of the transformations to grow and renew themselves, it has remained stationary or even recorded a decreasing trend in its productivity.

The fourth industrial revolution may, therefore, be an opportunity for the construction sector to reverse this trend. Entering the era of digitization and aligning with the key concepts of industry 4.0[23] can be seized as an opportunity for a profound renewal and overcoming of the internal barriers that hold back change.

The digitization of the construction sector is only just beginning, but there are signs that the situation is changing and the "Construction 4.0" idea is emerging.

22 Digitising the EU's Construction Industry. Manifesto Report. Jan-Mar 2019. https://www.euractiv.com/section/digital/special_report/digitising-the-eus-construction-industry/
23 Kagermann, H., Wolf-Dieter, L., Wahlster, W., 2011. Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. Industriellen Revolution. Nr. 13-2011 Seite 2 © VDI Verlag GmbH, Düsseldorf.

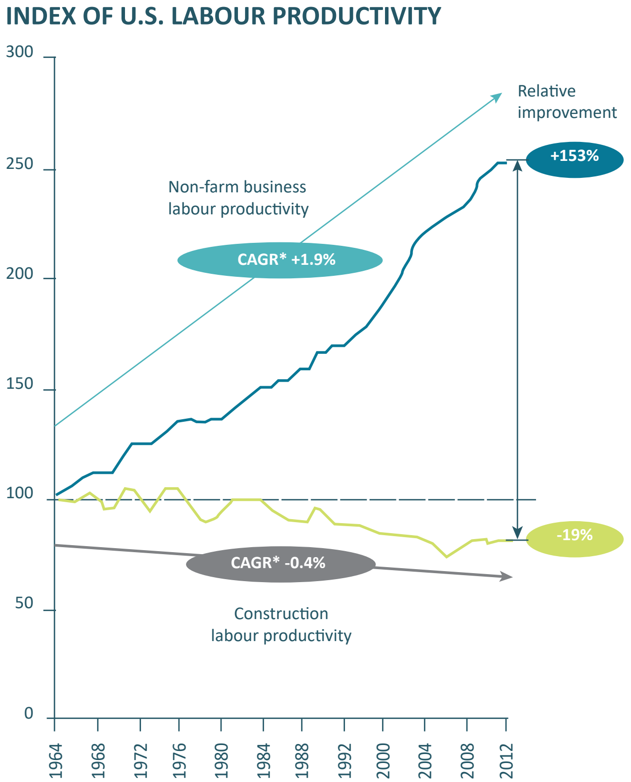


Figure 33 Labour productivity index in the United States, 1964-2012 (World Economic Forum 2016).

*CAGR Compound Annual Growth Rate

According to a study by the Association of German Chambers of Commerce and Industry (DIHK), 93% of companies agree that digitization will affect all their processes[24]. Investment in digital transformation has also begun in this sector, and there is a growing awareness that there are no alternatives to digital construction, as experts say.

Digital innovation in the construction sector indeed began with the spread of industry 4.0, but it can be assumed that there are also two new “motivating” conditions. On the one hand, an increasing demand for new ”tools” leading to their intelligent use to transform buildings into ”smart buildings”, ”smart districts” and ”smart cities”; on the other hand, the growing need to create - or recreate - conditions of well-being for humans and to actively contribute to the improvement of buildings with more environmentally friendly qualities.

24 Gerbert et al. 2016. *Ibid.*

The social and economic implications of the construction sector are important because its contributions in terms of impact on our lives, society, the economy, the environment, etc. are significant, as shown in Chapter 2, even small improvements will result in substantial environmental and human benefits for business and society. The economic influence on this sector brought by digitization, according to the Boston Consulting Group's 2016 report, within ten years will produce annual savings from $0.7 trillion to $1.2 trillion (from 13% to 21%) in engineering and construction and from $0.3 trillion to $0.5 trillion (from 10% to 17%) in operations[25].

The potential for improving productivity and efficiency through digitization, innovative technologies, and new construction techniques is also vast. Several new technologies are already available on the market, and many others are under development or still in the prototype stage, such as augmented reality, drones, 3D scanning and printing, Building Information Modelling (BIM), autonomous means, and equipment and advanced building materials. By adopting and leveraging these innovations, companies will increase productivity, simplify project management and procedures, and improve building quality and safety. Exploiting this potential will require commitment, effort, and investment in a wide range of areas, from technological development to long-term strategies or staff training or appropriate regulation.

3.2.2 Internal Resistance

In most countries, there has been little improvement in productivity in the construction sector over the last 50 years, especially when compared to other industrial sectors, as shown in Figure 33. Some new technologies and tools have emerged, but the rate of adoption of innovation has been prolonged. The causes and internal resistance slowing down the transition to the fourth industrial revolution are identified in the following aspects.

Research and Development (R&D) is the lifeblood of any activity or sector. Industries invest resources in R&D in order to improve and achieve long-term benefits. Research and Development has received less attention in the construction industry than in other sectors. Probably in this can be identify a first factor responsible for the lack of innovation and delays in the adoption of innovations in construction processes.

The construction industry operates in an environment that generally maintains a conservative and traditional corporate culture. The widespread perception is that construction companies are not sufficiently progressive or far-sighted, and for this

25 Gerbert et al. 2016. *Ibid.*

reason, reticence and stagnant investment in technological innovation are also a confirmation of this. Besides, there is a shortage of young talent and investment in staff skills development. The image people have of the construction industry as an employer is relatively weak, with insufficient gender diversity and job security.

Another internal brake factor within the sector can be identified in the unique and unique processes for each building construction and the insufficient transfer of knowledge from one project to another. Internal processes within companies are often based on informal, non-decoded activities. The insufficient rigor and consistency in the execution of the process are often due to the need and urgency to reach the final product to the detriment of the definition, study, and development phase of the process itself. This has a further impact on knowledge transfer. Although each project has its own unique and peculiar characteristics, it can be said that to a large extent, the design and construction processes are repeated in their essential elements from project to project. The lessons learned from a project could, therefore, often be usefully applied to subsequent projects, but few companies have institutionalised such a process and have the time and resources to do so. Therefore, experience is often lost and projects continue to depend mainly on the skills of the individual project managers and technicians involved. Furthermore, the peculiarities of the products in this sector, i.e. buildings, compared to those in other industrial sectors, making it difficult to monitor the entire process in order to analyse and optimize it. In many industries, individual operations are continuously monitored and large amounts of data are collected, while in the construction industry, this is more complicated and few construction companies are structured to do this.

Finally, one last aspect that needs to be highlighted is the level of cooperation between all the actors involved. Generally, the building process is a sequential activity that sees the involvement and contribution of different figures: project owner, designers, builders, suppliers, etc. Ideally, therefore, knowledge of all stakeholders along the value chain should be fully exploited from the very beginning of the design and planning process, but this is rarely easy or even possible under current arrangements. Also, economic and market mechanisms influencing choices and decision-making processes in terms of collaboration strategies, tendering, and purchasing.

3.2.3 Standard and Policies Framework

The new landscape, the renewal of the other sectors, customer demand for new products and the spread of new technologies, with the consequent natural reduction in costs, are just some of the reasons that could lead designers, companies, and construction companies to embrace the fourth industrial revolution. One of the main factors that have been, and continues to be, decisive is the State support; a national government can influence the construction sector in various ways, for example, it is the guarantor of the health, safety and environmental conditions of the workers involved in the building process and the people who use it. It can also have a direct impact on businesses, strategies, and support market competition at the national and international levels. Therefore, appropriate government policies, the development of a specific regulatory framework, and funding plans must be in place to guide and support this transformation.

A comprehensive framework consisting of well-designed standards, transparent and streamlined authorisation procedures, is the key to success, effectiveness, and compliance. Avoiding overlapping standards and high fragmentation between different levels - international, national, and local - are just some of the objectives pursued in this area in recent times. The Eurocode initiative[26] is an example of what has been done to harmonise structural design standards across Europe. This set of standards makes it possible to have common calculation criteria that can be adopted in all Member States and also to have a single reference for the declaration of performance of prefabricated construction products. In addition to this type of international standards, there are also national and local standards that allow greater detail and specification based on the peculiarities of each territory, such as the characteristics and traditional local building particle or requirements related to geography and climatic conditions.

The regulatory framework needs to be updated and adapted to reality and the market and to reflect economic, social, and technological changes. The EU-level strategy set out in the document published in 2012 as part of the Europe 2020 initiative[27] has been developed on this concept. It is a communication strategy for the sustainable competitiveness of the construction sector and its enterprises. The document focuses on promoting favourable market conditions for sustainable growth in the construction sector. Five areas are addressed:

- financing and digitization: in particular for energy-efficient investments in building renovation and for research and innovation in a smart, sustainable and inclusive environment;

26 The EN Eurocodes are a series of 10 European Standards, EN 1990 - EN 1999, providing a common approach for the design of buildings and other civil engineering works and construction products. More information are available on https://eurocodes.jrc.ec.europa.eu/

27 The Europe 2020 strategy is the EU's agenda for growth and jobs for the current decade. It emphasises smart, sustainable, and inclusive growth in order to improve Europe's competitiveness and productivity and underpin a sustainable social market economy.

- skills and certifications: training of the workforce and management to create jobs through skills and apprenticeships to meet the demand for new skills;
- resource efficiency: focus on low-emission construction, recycling and valorisation of construction and demolition waste;
- regulatory framework: emphasis on reducing the administrative burden for businesses, in particular, SMEs;
- international competition: encouraging the adoption of Eurocodes and promoting the dissemination of new financial instruments and contractual arrangements in third countries.

Committee for European Construction Equipment (CECE) for the European elections last May 2019, published an appeal for the next legislature on concrete actions and critical areas to be considered for the future of European policies. These included a call to support the digitization of the European construction industry. Also, the EU's long-term budget for 2021-2027, called "Digital Europe", is setting aside €9.2 billion to fund technological projects, including supercomputing, Artificial Intelligence, cybersecurity, digital skills and support for companies to better digitize their business processes.

Other examples can be found in the UK and the German Government's plans for environmental concerns and the emergence of new digital tools, such as Building Information Modeling (BIM). In the UK, the Government in 2011, with the "Government Construction Strategy"[28], sets the BIM standards (Level 2) for 2016, and then revised and raised the target to maximum digital integration and connectivity (BIM Level 3)[29] by 2020 with the new version of the "Government Construction Strategy 2016-2020". (2017)[30]. In the German case, however, the Federal Ministry of Digital Infrastructure and Transport has drawn up the "Planen-Bauen 4.0"[31] to guide the development of a strategic BIM Roadmap for the German construction industry.

28 Available on the website: www.gov.uk/government/publications/government-construction-strategy

29 BIM Levels will be described in section 3.3.

30 More information available on www.gov.uk/government/publications/government-construction-strategy-2016-2020

31 Further information available on www.bmvi.de/SharedDocs/DE/Publikationen/DG/stufenplan-digitales-bauen.pdf?__blob=publicationFile

32 The document since its first publication has been updated several times: twice in 2017 with the "corrective" Decree of 19 April 2017, n.56 and the Law of 27 December 2017, n.205; in 2018 with the "simplifications" Decree of 14 December 2018, n.135; and finally, several times this year. Today we find it in version 7.3 of July 2019, which contains the latest update due to Law no. 58 of 28/6/2019 converting the so-called "Growth Decree".

In the Italian context, although with severe delay, some initiatives promote and support industry 4.0 and the construction sector innovation. The European Directive 2014/24/EU on public procurement, in which Member States are required to adopt BIM in the public sector by 2016, has been implemented in Italy by D.Lgs 50/2016 - Code of Public Contracts[32]. Its aim is not only to implement the Directive but also to renew the public procurement system in Italy thanks to the use of digital tools to make it more trasparent and more straighforward, with more efficient and professional contractors and a more coordinated and functioning system of controls. The document established these key concepts, and then details are settled by "Decreto Ministeriale 560/2017"[33] published by the Ministry of Infrastructure and Transport. This document, also known as the "BIM Decree", defines the methods and timing for the progressive and mandatory introduction of specific electronic methods and tools in public procurement.

The issue mentioned above concerning control mechanisms and sanctions is a crucial element for the success and verification of the correct application of legal measures in order to better protect public health, improve safety and safeguard the environment. In many developing countries, 60-80% of buildings continue to evade any form of control over the building environment, resulting in a precise exposure to significant risks and costs to the community[34]. In the United States, the Hurricane Katrina damage assessment team concluded that one of the main reasons for the extent of the devastation of buildings along the coast was the buildings' non-compliance with current regulations. Therefore, the investment required for the strict implementation of the standards and their verification can lead to a direct benefit, not only at the government level but especially for individual citizens. Some American studies carried out on the economic impact of regulations show that, for example, in the area of energy efficiency, every dollar spent to strengthen standards will return six dollars in terms of energy savings[35].

Finally, the financial support of the transformation process by national governments is necessary to create a more fertile environment for the development of technological innovations by providing adequate support to academia and business. There are many plans adopted throughout the world, examples of which are given below:

- the U.S. Department of Transportation has for years been funding hundreds of research projects to improve the design, construction and operation of in-

33 Decreto Ministeriale n. 560 del 01 dicembre 2017.
34 World Economic Forum, 2016. *Ibid.*
35 Vaughan, E., Turner, J., 2013. The Value and Impact of Building Codes. Environmental and Energy Study Institute White Paper.

frastructure, roads, tunnels, and bridges for nearly $500 million through various funding lines in individual areas[36];

- Singapore, through the "Construction Productivity and Capability Fund" of around $800 million, is helping the construction industry to improve productivity and strengthen its capabilities[37]. For example, part of the cost of purchasing BIM software/hardware and related consulting and training; the cost of equipment and machinery that improves productivity by at least 30%; or the cost of developing projects on process innovations.
- Italy, together with the Ministry of Economic Development, has developed a "National Industry Plan 4.0" of financing, equal to 48 million euros in 2019, for all companies that want to seize the opportunities related to the fourth industrial revolution. It is based on three main guidelines: operating in a logic of technological neutrality, intervening with horizontal actions, and acting on enabling factors[38].

3.2.4 Digital Innovations in practice

Digital transformation of the construction industry towards Construction 4.0 has been triggered in an already complicated picture of global challenges that this sector is facing today, such as climate change, the security of energy supply, the growing need for renewable energy sources, energy poverty, global competitiveness.

Set of digital technological innovations, which cross and connect the construction sector with other sectors and services (Figure 34), and the increased focus on the sustainability of construction has created a growing diffusion of the term ″smart building″. The concept of "smart buildings" is continuously evolving and stems from the change, destined to continue, of the built environment towards more dynamic habitats able to guarantee comfortable living and working environments for the occupants.

Although the term "smart building" is now widely used, the focus on that can be traced back to the early 1980s in the United States. At that time, the "Intelligent Building Institution" described an intelligent building as "one which integrates various systems to effectively manage resources in a coordinated mode to maximise: technical performance; investment and operating cost savings; flexibility"[39]. Since then, the concept has been expanded and modified based on the megatrends that are having a substantial impact on the built environment as we know it (Figure 35).

36 Budget Highlights 2020. www.fhwa.dot.gov/cfo/dot_bh2020_030719final.pdf
37 More information available on www.bca.gov.sg/CPCF/cpcf.html
38 Further information available on www.mise.gov.it/index.php/it/industria40

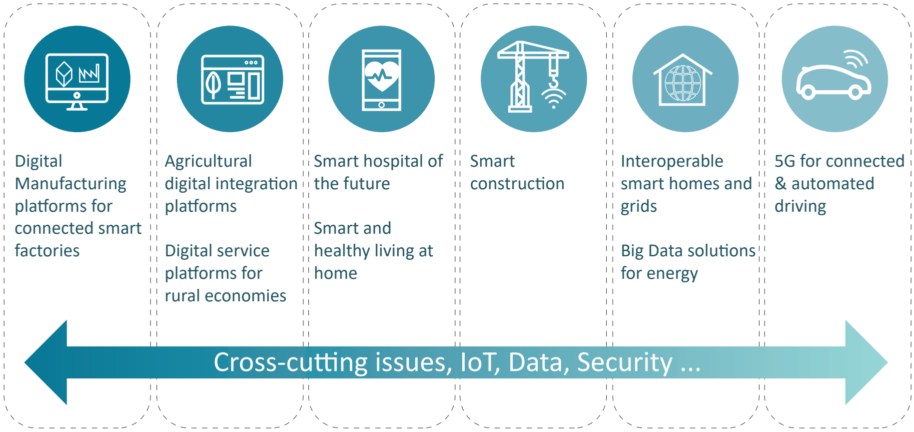


Figure 34 Cross-cutting innovation through different activities (EU 2017).

The original idea of intelligence, within an elementary building, has now become much more advanced and sophisticated. It has come to have the common perception of an intelligent building as an interconnected, flexible, automated, energy-efficient, and secure system for occupants. The next step, towards which it is moving, is that of environmental intelligence - a building that is sensitive and responsive to the needs of the occupants and the energy system. It will be a building that recognises people and automatically adapts to the behaviour and preferences of the occupants, thereby optimizing comfort, safety, energy use, and well-being[40].

An intelligent building can also be considered highly energy-efficient, thanks to the use of new technologies as new way to manage and respond to its energy demand. An intelligent building: stabilises and drives a faster decarbonisation of the energy system through energy storage and demand flexibility; gives users and occupants control over energy flows; recognises and reacts to the needs of users and occupants in terms of comfort, health, indoor air quality, safety and operational requirements[41].

39 Ghaffarianhoseini, A., Berardi, U., AlWaer, H., Chang, S., Halawa, E., Ghaffarianhoseini, Ali, Clements-Croome, D., 2016. What is an intelligent building? Analysis of recent interpretations from an international perspective. Architectural Science Review 59, 338–357. https://doi.org/10.1080/00038628.2015.1079164
40 De Groote, M., Volt, J., Bean, F., 2017. Smart Buildings Decoded. Buildings Performance Institute Europe (BPIE).
41 De Groote et al. *Ibid.*

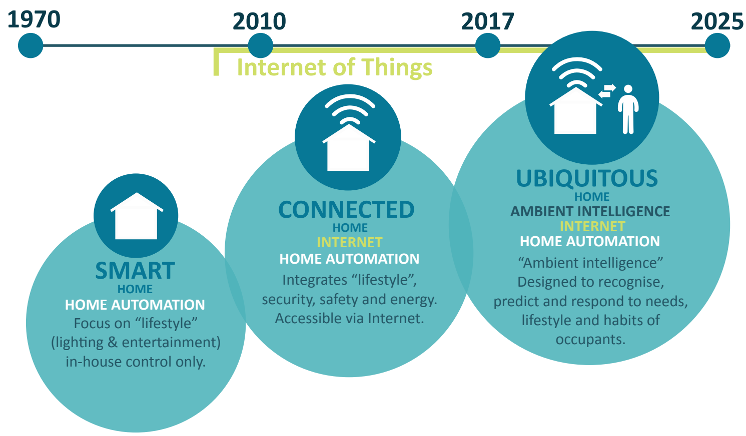


Figure 35 Evolution of connected and smart homes (BPIE 2017).

Intelligent buildings can radically change the role of building stock, including new functions and providing valuable services to occupants and energy systems. What we consider intelligent today was not even imaginable just a few decades ago, but rapid innovation has provided technologies and initiatives that demonstrate how smart buildings can become in the not too distant future[42].

The technologies used inside buildings are multiple and allow an advanced analysis to improve their management. Thanks to real-time access to precise data, collected through sensors, cameras, or 3D laser scanners, it is possible to monitor buildings continuously, and at the same time, carry out predictive maintenance, thus reducing the number of manual inspections and unexpected problems or inefficiencies. In addition, the data collected can be fed into a BIM model, which is therefore updated continuously and can help designers, engineers, and maintenance staff to assess the impact of, for example, redevelopment work or the implications of any other decisions regarding the life of the building. The possibility of creating a model, or instead, it could be called a building database, allows the management and maintenance phase to be transformed and made more efficient and can also be defined as smart.

By shifting the attention also to all the other phases of the entire building process, we can already see other transformations that the use of the fundamental principles and technologies for the digital transformation process have generated (Figure 36). Today it is already possible to speak of "Construction Site 4.0" for the construction phase of the work in which they are used:

42 De Groote et al. *Ibid.*

- **real-time data sharing, integration, and coordination of all stakeholders**
  During the construction phase, one of the biggest challenges is to provide the right information to all stakeholders, contractors, and subcontractors, at the same time and in the same place. BIM models shared in the cloud can be one of the tools that can be used by all people to share data in real-time, for integration and coordination of activities. Coordination, often an element of weakness and fragmentation, thus becomes a strength and efficiency.
- **Construction site planning**
  The use of project management tools, data contained in tags based on RFID[43] technology, and the collection of Big Data allow you to organize the site better and plan the use of resources.
- **New construction methods**
  The new digital building models contain detailed information that can facilitate the use of new approaches to construction, including prefabrication and 3D printing. This results in several benefits such as better sequencing of construction phases, reduced time and delays, a safer environment for workers, and improved materials.
- **Automated and autonomous construction**
  Robots and intelligent machines improve productivity, precision, and safety on site. Remote control systems and 3D driving models enable high levels of automation, comparable to numerical control systems in the industry.
- **Strict construction monitoring and surveillance**
  Digital meters and monitoring devices allow companies to control the construction process and activities with greater rigor. To limit errors and changes, 3D laser scanning is continuously used to compare the construction with the digital model. Drones and cameras also monitor and supervise the construction site.

43 The acronym RFID comes from the English "Radio-frequency identification". In telecommunications and electronics, it means a technology for the automatic identification and/or storage of information relating to objects, animals or people based on the capacity of data storage by particular electronic tags, called tags, and the ability of these to respond to remote interrogation by special fixed or portable devices, called readers.

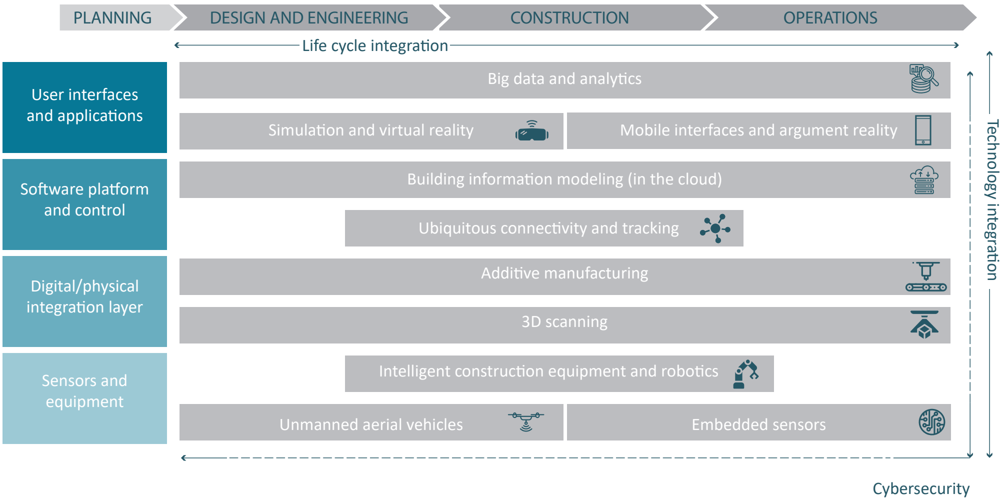


Figure 36 Digital technologies implemented in the building process (Gerbert et al. 2016).

Digitization has also brought some transformations to design and engineering of the project, although the most substantial advantages are those previously described for the construction, management, and maintenance phase. Among innovations in this phase are:

- **Architectural design and parallel engineering**
  Building Information Modeling makes it easier for architects and engineers to approach and cooperate, helping them to share their work and combine digital models, identifying interdependencies, contrasts, and quickly assessing design iterations.
- **The virtualisation of physical structures**
  Aerial mapping technology and 3D laser scanning can be used to convert existing buildings and infrastructure into virtual 3D models. This not only brings advantages for the design of new buildings but also favours renovation and retrofitting projects by increasing accuracy and saving time compared to manual measurement and surveying.
- **Data-Based Design**
  The design based on the analysis of Big Data, such as behaviour of people or infrastructure environment, allows the optimization of design decisions and then improves their effectiveness and operational efficiency.

- **Simulation and prototyping**
  New modeling techniques, such as enhanced simulation through holographic technology or prototyping with 3D printed models, speeds up design, and provides techniques and tools for its preliminary visualization.
- **Iterative planning**
  Software tools integrated with BIM provide several advantages, such as automatic generation and evaluation of design alternatives, improving the preliminary analysis of different aspects such as cost, timing, or sustainability.

Combining all these technological innovations in the individual stages of the construction process can contribute to defining a new Construction 4.0 framework in the era of digitisation (Figure 37). It highlights the new technologies used and the connections with other sectors and issues related to the circular economy, the preservation of resources, or the new logistics 4.0 that connects the industries that provide the means, materials, and technologies with the construction sector.

Digital transformation is driven by a shift towards a direct connection between the physical world and the digital one. The new scenario highlights how the integration of these two worlds has led to the emergence of building information models that bridge the gap between real and virtual: design intentions, architectural concepts, and material execution. The key technological innovations, described at the beginning of this chapter, are declined in construction as autonomous vehicles, advanced robotics, 3D printing, new materials, Big Data, Internet of Things (IoT), virtual reality, augmented reality, and Building Information Modeling.

However, which among all these technologies is the one that more than the others allow the entire construction sector to innovate by challenging its traditional processes?

Building Information Modeling seems to be the answer to this question. The World Economic Forum has carried out an in-depth analysis and map of global technology trends that drive change and their impact on the sector through the "Future of Construction" project, which aims to support the engineering and construction sector in the transformation process. The results of this project are summarized in the report "Shaping the Future of Construction"[44]. In this document, the impact and probability matrix of the advent of the different technologies is presented, and it shows that BIM is the one with the highest values (Figure 38). In addition to this result, it is possible to find other sources and studies that confirm that it is the key-

44 World Economic Forum, 2016. *Ibid.*

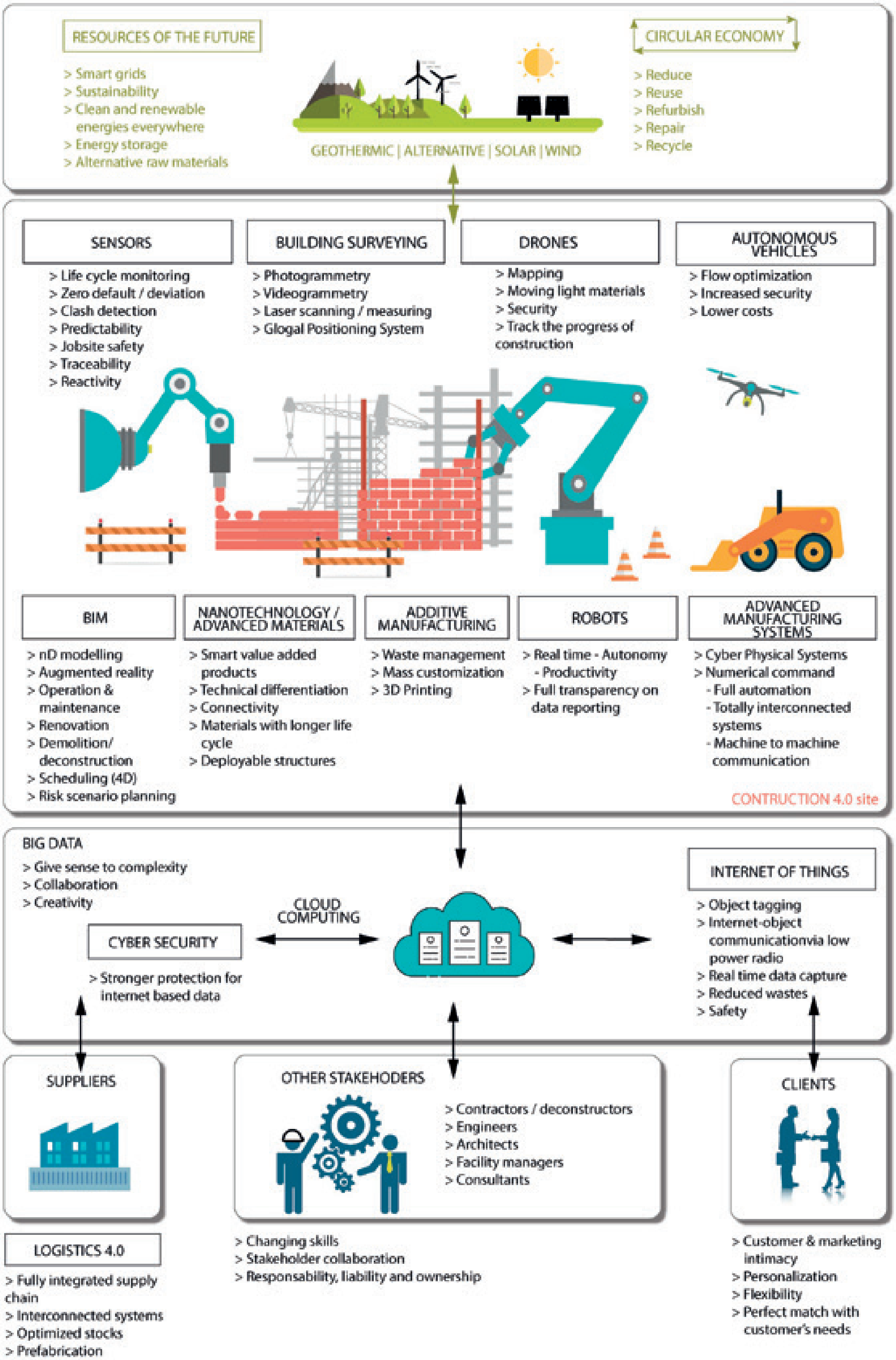


Figure 37 Construction 4.0 framework. (Craveiro et al. 2019)

stone of the "revolution" of Construction 4.0, supporting the entire building process throughout the life cycle and being able to connect and accommodate all the data and innovations of other new digital technologies.

In the following paragraph, therefore, the topic of BIM will be discussed in-depth, presenting its main characteristics, the standards framework, and the current degree of diffusion and development.

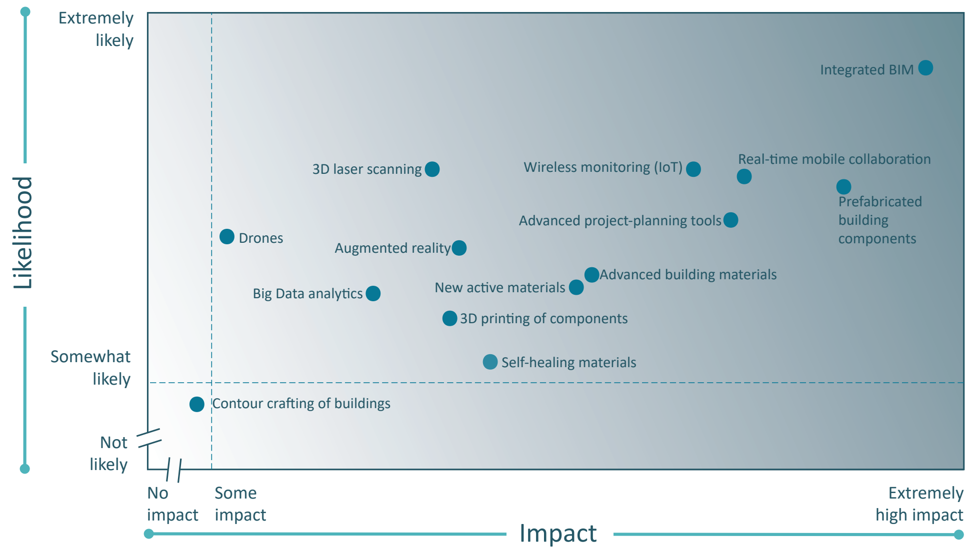


Figure 38 Future Impact and Likelihood of New Technologies (World Economic Forum 2016).

3.3 Building Information Modeling

The debate about "what", "how", and "why" Building Information Modeling is influencing the construction industry is exstensive. A quick online search for the terms "building information modeling" or "bim" produces more than 200 million results and it is clear that there is no lack of information on BIM. The real difficulty, however, is to sift through the vast amount of information available to get a good idea of how the construction industry is revolutionizing. We talk about radical change, technologies, people, and processes. There is information on government programs that support transformation, new global and local standards, and much more. Finally, many different definitions and words are corresponding in particular to the M of the acronym. All this is the most significant proof that the concept of BIM is continuously evolving.

Today "Building Information Modeling" version is the most used, but the acronym BIM has undergone a process of maturation and changing its meaning over time. The association of different words to the letter M derives from the desire to emphasize the aspects that, from time to time, have seemed to be more characterizing. Words such as Model, which reflects the initial perception of BIM as a tool for the creation of a virtual model, and Management, this time referring to the organization, management, and control of processes concerning the product, have been used.

Among the many definitions that can be found are the two most widespread and which are more focused on the life cycle of the building aspect (Figure 39). The first is the one given by NBIMS-US[45], which defines BIM as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward".

The second is the one given in the English standards, which form the basis of the ISO 19650 currently in force and which will be further explained later: "Building Information Modelling (BIM) is a collaborative way of working underpinned by digital technologies, which allow for more efficient methods of designing, delivering and maintaining physical built assets throughout their entire lifecycle. Greater efficiencies can be realized due to significant pre-planning during the design and construction phases, providing comprehensive information at handover stage."

45 The National BIM Standard-United States® (NBIMS-US™) is a project committee of the National Institute of Building Sciences (NIBS) that provides consensus-based standards through referencing existing standards, documenting information exchanges and delivering best business practices for the entire built environment. NIBS is an institute that brings together a group of building industry professionals, in addition to government, non-profits, private sector, and academia, to develop solutions to the challenges faced in the built environment.

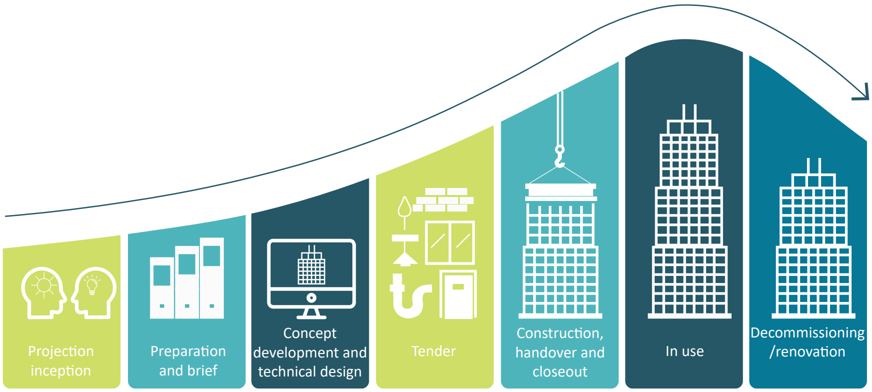


Figure 39 Lifecycle concept applied to the built asset (RIBA Plan of Work 2013).

The difficulty in researching and being able to report a unique definition further underlines the state of evolution and research still in progress in this area. From all definitions, however, emerge some common concepts at the basis of BIM: BIM is progress and advancement of CAD that has a high component of collaborative work that will lead to technological innovation, and that will change the whole process and the way of approaching the work. Its implications are, therefore, not only technological but also methodological. Among the various levels and aspects of the built environment sector on which it affects, the following can be highlighted:

- the continuum of people, projects, companies and the whole sector (Figure 40);
- the whole life cycle of the project and the general world view of the main actors involved (Figure 39);
- the links between BIM and the "operating system"[46] of the built environment;
- the way the project is implemented, influencing all its processes.

BIM covers all aspects, technologies, and people involved in the construction sector. It can be defined as a catalyst element, which has resulted in a rethinking of the way construction design conduction of the built environment[47]. A key element of BIM is the "I" of the acronym, i.e. information and data. It is a mechanism that allows the

46 Howell, G. A., Ballard, G., Tommelein, I., 2011. Construction Engineering—Reinvigorating the Discipline. Journal of Construction Engineering and Management 137, 740–744. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000276
47 Sawhney, A., Singhal, P., 2013. Drivers and Barriers to the Use of Building Information Modelling in India. Int. J. 3D Inf. Model. 2, 46–63. https://doi.org/10.4018/ij3dim.2013070104

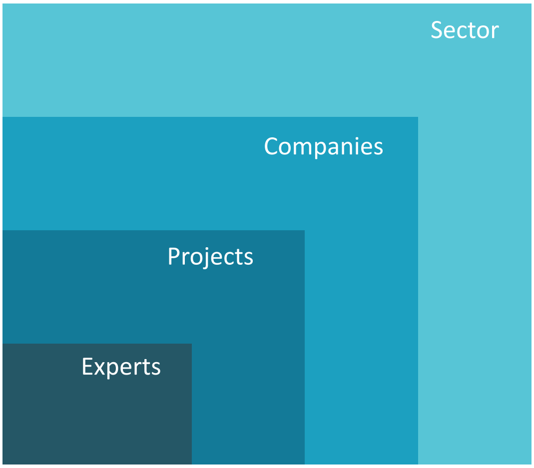


Figure 40 BIM implications in different areas of the construction industry.

creation, storage, and sharing of information in a new way, one might say "revolutionary" and far superior to all other systems currently in use. As Chuck Eastman says, the BIM process is revolutionary because it offers the opportunity to migrate from practices centered on social skills to higher, more advanced mechanical skills - with all the implications of the case[48].

It is in work begun 50 years ago, by Charles M. Eastman, or better known as Chuck Eastman[49], that one can find the basis and concepts of design approaches based on Building Information Modeling. In 1974, in fact, with "An Outline of the Building Description System"[50] text, he laid the conceptual foundations of today's BIM. In his research report, he described an innovative vision for a computational system conceived for the historicization and manipulation of detailed information of a project. The nature of this information had to be such that it could facilitate several characteristic phases of a project, from its conception to construction and management. The system described by Eastman was baptized by him "Building Description System" and was built on an underlying belief that he intended to consider any constructed artefact as a progressive "composition of a set of parts". The result of this belief was the need to manage this organism through an ordered and structured system.

48 Eastman, C., 2009. What is BIM?
49 Professor at University of Architecture and Computer Science at the Georgia Institute of Technology, Director of the Georgia Tech Digital Building Laboratory and holder of numerous awards in the fields of Design Intelligence and Open Data.
50 Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D., Yessios. C., 1974. An Outline of the Building Description System. Research Report No. 50. Univerisity of Pittsburgh Carnegie-Mellon, Pennsylvania.

Eastman desired to find solutions to specific needs that the construction sector had begun to manifest a few years before. What he then defined as "The problem" was the lack of economic optimization (and of resources in general) of a project mainly due to real material impediments. According to Eastman the process that from the concept ideas leads to the realization of architecture, by its very nature, is characterized by impediments, criticalities, and widespread weaknesses. Considering that at the time of the document, as it still is today, the pricipal means for the exchange of information concerning a project consisted of graphic elaborations of various kinds, the need for multiple representations for a complete description of the design idea is immediately evident. Also, the management and continuous updating of the drawings required a high expenditure of time and resources.

"A large effort is also directed at keeping current the information in the set of drawings for a building project. But even with this effort, at any moment, at least some of the information depicted by a drawing is not current or not consistent. Thus, decision making by one group of designers may often be based on obsolete information, further complicating their task"[51].

After decades from the first Eastman publications and this analysis of the situation and its related problems, it is possible as designers and researchers to find themselves in his words, and the issues he described seem to be very current and still to be solved. BIM is, then, the panacea or revolution that the sector was waiting for? It is difficult to answer. Indeed, all the changes, which have been briefly introduced and will be further investigated later, are theoretically allowed by the introduction of BIM. They are, however, subordinate to technological developments and even more so to the ability of the project team to elaborate and of all the other technicians involved in the construction lifecycle to use information-rich, high fidelity models.

3.3.1 BIM Revolution

Building Information Modeling today can integrate, in a unique and shared model, the set of processes and information used for design, implementation, and management, through models created by all participants in the building process, at different times and also for purposes not equal to each other in order to ensure quality and efficiency throughout the life cycle of the product. This peculiarity and revolutionary feature for the construction sector is the result of a long process of evolution that has transformed both the tools and techniques and the process itself and comes from a critical element: interoperability.

51 Eastman et al., 1974. *Ibid.*

The concept of interoperability is at the basis of BIM. It allows the complete sharing of information of the different specialist fields allowing to export, from the single BIM model, the different models of the various disciplines in their calculation environments to carry out analysis and possible design changes. The model created in BIM can, therefore, be considered a "source" model for the technicians involved in the design and, more generally, for all the operators in the sector who, with extreme simplicity, can draw from the source file mentioned above, unique and shared, all the characteristics necessary for their specialist field. Every modification or integration made to the project, by the single operators, is simultaneously transferred to the central model to minimize the loss of information, during the design phase, and to evaluate any criticality between the congruence of data and the different design levels. Given these peculiarities and potentialities, it is not possible to define BIM as new technology or software but as a new working methodology to support the whole building process and for all the participants in the construction industry.

The correct application of BIM, in each phase of the project life cycle, is closely linked to two aspects that are the basis of the methodology: the interoperability between the different software applications and the Level of Detail (LOD) of the model of the work achieved. It is from the union and the optimization of both that the BIM can provide global support to the construction work development and management. When we talk about different levels of use of BIM, levels of maturity, and degree of interoperability achieved, we often find the scheme of the Bew-Richards triangle[52] contained in PAS 1192-2:2013[53] (Figure 41). The scheme represents the evolution and technical and collaborative progress of BIM through an index based on four levels of maturity. Specifically, they are:

- Level 0 corresponds to a low, or even absent, collaboration and, consequently, the absence of a shared information environment between the various actors involved in the project process. At this level, only 2D drawings are used, which can be issued and distributed in the paper, digital raster, or mixed paper/digital form. Modifications and variants must be made several times and updated in each work.
- Level 1 corresponds to a level of maturity in which cooperation, although only partially, is present. Interoperability begins to be formally managed, with the increasing introduction of spatial coordination functions, standardized structures, and formats, although the models are not yet shared between the fig-

52 Bew, M., Richards, M., 2008. Bew-Richards BIM maturity model, BuildingSMART Construct IT Autumn Members Meeting, Brighton.

53 PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling. Status: Withdrawn.

ures taking part in the project. One can simplify the concept by thinking that level 1 BIM includes a set of 3D models without information, used for visualization purposes, and 2D tables used instead for documentation and production data.

- Level 2 is achieved when there are collaborative work and data exchange between the disciplines involved (architectural, structural, plant engineering, energy, management, etc.). Each professional involved can actively contribute to the BIM model called "federate" (Figure 42), obtained thanks to the union of the models and the various information produced by the individual technicians and on which it is possible to conduct real-time controls. This is the level concretely reached in large part of the international scenario, including the United Kingdom. Level 2 is the goal set for the Italian context.
- Finally, with Level 3 the full collaboration of all parties takes place through the use of a single shared project model, stored in a single centralized database: all subjects can access the same model and modify it, thus avoiding the final risk due to contradictory or conflicting information that may arise in the phase of joining the models present in Level 2.

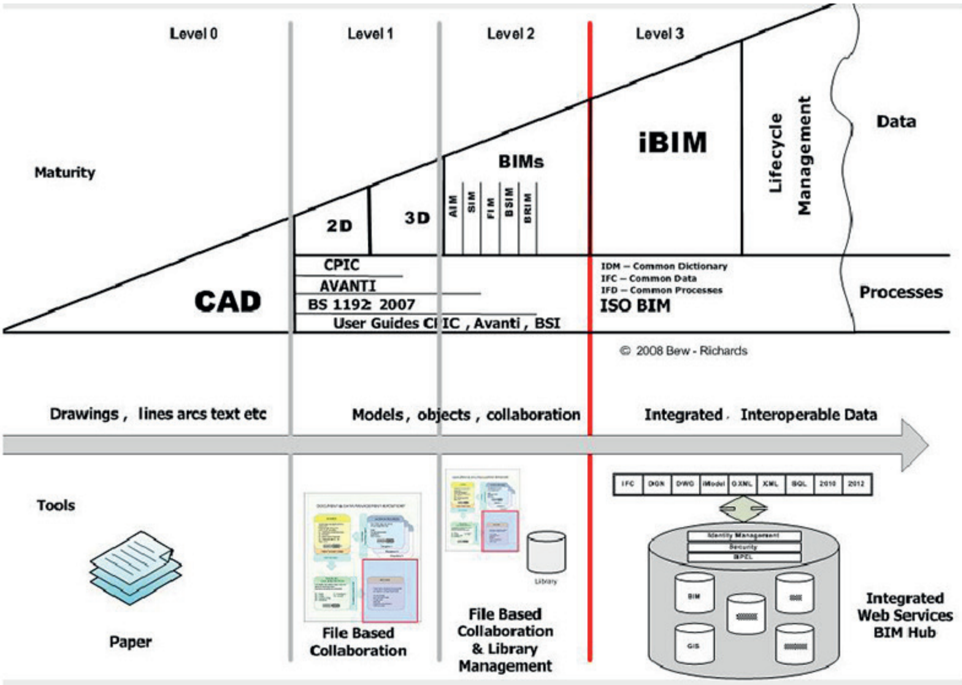


Figure 41 Bew-Richards Triangle of BIM maturity levels and implementation of the collaborative process over the years (Bew and Richards 2008).

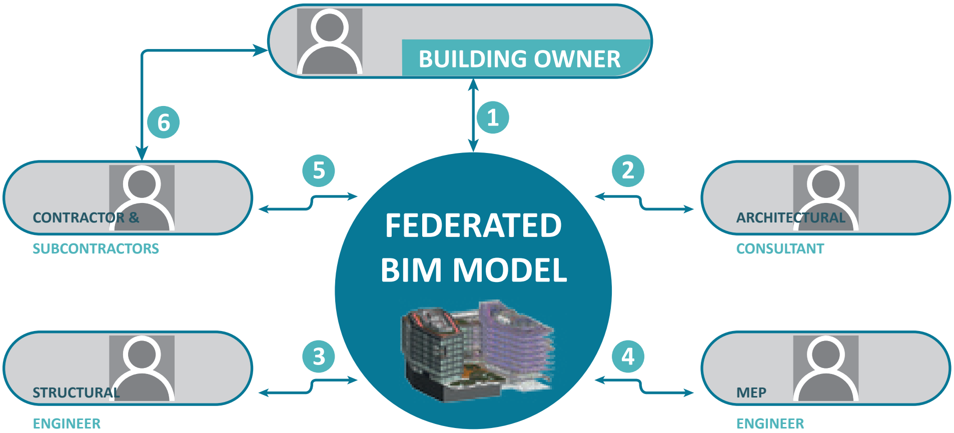


Figure 42 Diagram of a federated model and information flow (RICS 2014).

The BIM adoption and the levels of maturity achieved are not uniform throughout the sector and in different countries. Although the Bew-Richards framework described the completion of BIM Level 3 by 2020, this is not yet achieved even in the most advanced countries in the field of BIM.

In the latest book on Building Information Modeling[54] of Chuck Eastman, the graph prepared by the Building Informatics Group at the University of Yonsei in Seoul (South Korea), which briefly outlines a new trajectory for BIM until 2030 (Figure 43). In this graph, albeit with new names, we find the levels defined by Bew-Richards: from BIM 0.0 until the end of the current decade (20's) where we find the Full BIM - BIM 3.0 which corresponds to the BIM level 3 also defined in the series of English standards BS PAS 1192 and other BS documents. The next two steps are foreseen in this (2020s) and the next decade (2030s) are called respectively Lean BIM - BIM 4.0 and AI BIM - BIM 5.0.

"Lean BIM" is a term used for the practices envisaged in the decade just begun, which is based on the operational strategy "Lean Thinking", originating from the automotive world and in particular from the Toyota Production System (TPS). It revolves around the basic principles of continuous improvement (kaizen) and respect

54 Sacks, R., Eastman, C., Lee, G., Teicholz, P., 2018. BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers. John Wiley & Sons.

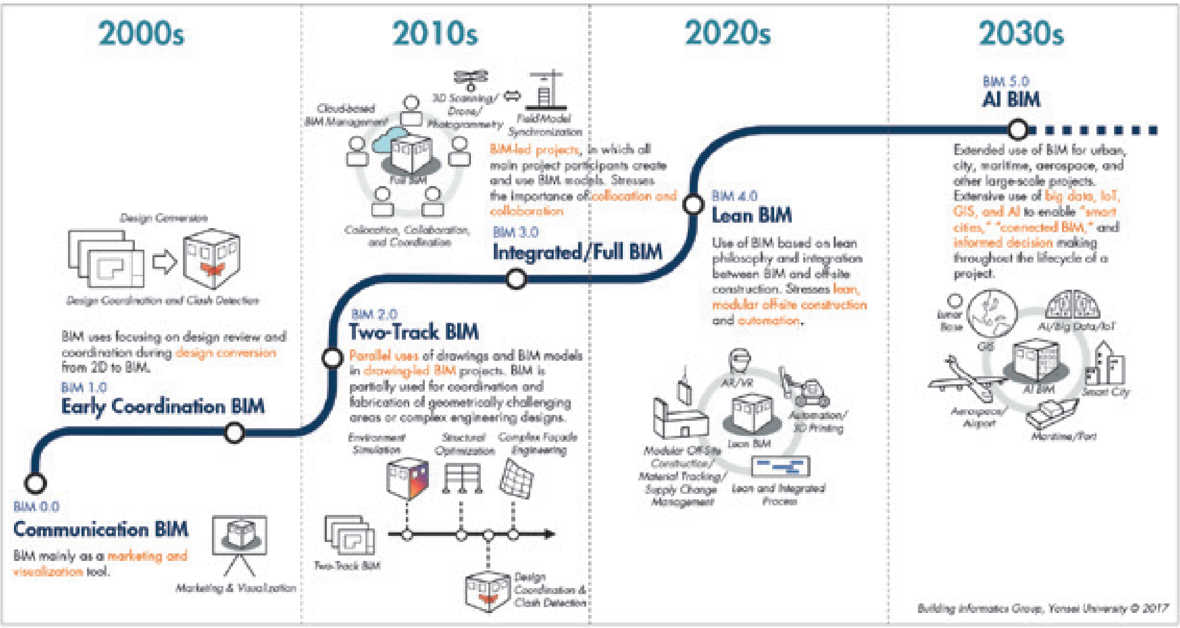


Figure 43 BIM progression through the decades (Sacks et al. 2018).

for people. With this approach, which questions everything and embraces change, an organisation, even an entire sector, can systematically adopt the principles of Lean in their core business processes[55]. Waste reduction and tools used for this purpose can be seen as a superficial simplification of lean principles that go much more profound. The construction industry is adopting them, and the following definition can also be found on Lean Construction: the pursuit of continuous and contextual improvements in the design, procurement, construction, operation, and maintenance processes to ensure value for all actors[56]. From this definition, it is even better to see how this philosophy is appropriate and can be quickly declined in the BIM field for greater integration and automation of off-site construction. The use of Lean and BIM in synergy will allow to improve and streamline the management of higher flows of information, materials, equipment, spaces, people belonging to the design and construction teams.

55 Sawhney, A., 2011. Modelling Value in Construction Processes Using Value Stream Mapping. The Masterbuilder - October 2011. www.masterbuilder.co.in. 88.
56 Michigan State University, 2006. The Construction Industry Research and Education Center (CIREC).

The following decade, corresponding to the 2030s, is defined as the "AI BIM" period. It is expected that there will be substantial changes in the way BIM is applied as a result of the increasing use of AI in society in general and its application in construction in particular. The extensive use of BIM for the different areas of construction - urban, city, maritime, aerospace and other large-scale projects - combined with the extensive and intensive use of Big Data, IoT, GIS, and AI will allow the concepts of "smartcities", "connected BIM" and "informed decision making" to be pursued throughout the life cycle of the construction process.

BIM Dimensions The evolution of BIM, in addition to increasing maturity levels, increases the number of aspects considered and included in the process and tools used (Figure 44). It is commonly defined these aspects as "dimensions" of BIM - 2D, 3D, 4D, 5D, 6D, and 7D - and each of them corresponds to a specific aspect of the building process.

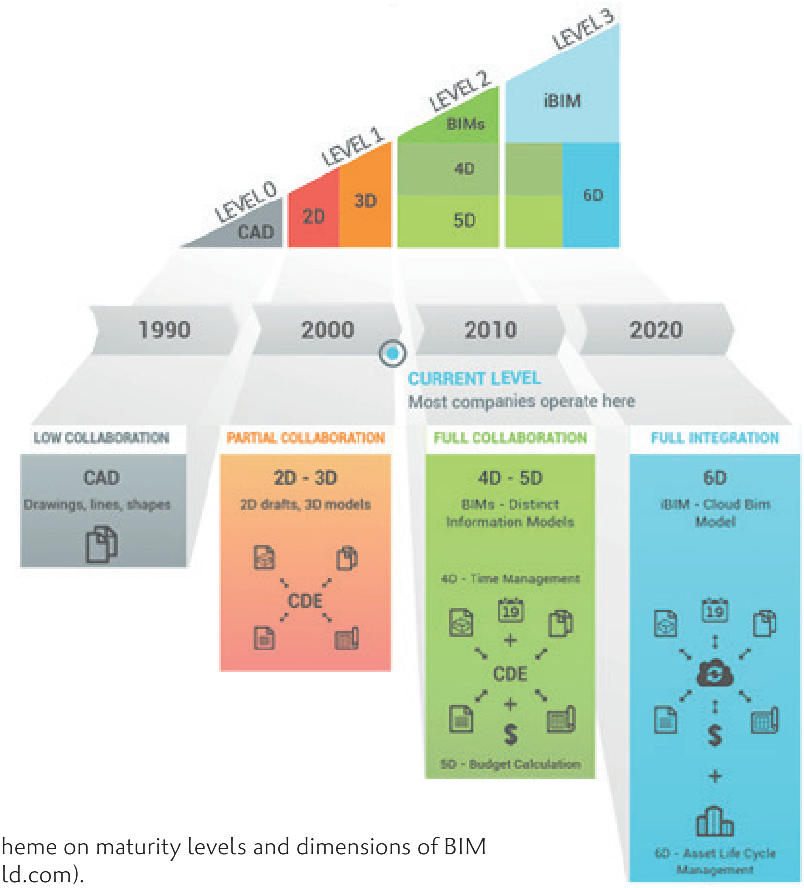


Figure 44 Scheme on maturity levels and dimensions of BIM (www.letsbuild.com).

The 2D and 3D dimensions correspond to the geometric aspects of the project and are included in Level 0 and Level 1 of BIM. In this context, BIM is used as a CAD tool for 2D designs, or as a 3D modeling tool able to manage only the geometric information of the project and to identify any discrepancies or “clashes” between the models generated by the individual disciplines. This control is done through the activity known as “model-checking”, which is formalized in two distinct operations: “code checking”, i.e. the verification of the adherence of the model to the design and regulatory requirements, and “clash detection”, i.e. the preventive analysis of conflicts, geometric and not, present in the model.

BIM 4D allows for the integration of time aspects. It can manage the scheduling, the division, and breakdown of the project into simple tasks, visualize the progress and status of the work at any given time. This is possible by associating one or more specific elements in the model to each site activity, defined in the schedule and represented by a Gantt diagram. In this way, all the changes in the BIM model will have an impact on the construction schedule and, at the same time, the model itself will be able to automatically identify those changes that will affect the sequence of scheduled activities that determine the duration and completion times of the work.

BIM 5D allows managing costs. One of the fundamental elements for its success is the extraction of the measures from the project to define the necessary quantities of materials. In traditional design, the production estimation (costs/revenues or parametric production index) starts with the digitization of the paper project documents, or the import of CAD drawings into a resource estimation software, or by manually extracting the quantities from these documents. All these methods lead to potential and inevitable human errors. Using a BIM model, instead, it is possible to extrapolate from the model the quantities associated with the single work activity and related to resources and equipment (understood as materials, labour and subcontracting) as elements of the construction process of the single activity to which it is possible to associate different values and thus obtain an estimate to support the management model of the work. It is possible to obtain indices and values related to: “physical progress” divided by “Total by Activity” or “Individual Activity”, in addition, of course, to the completion and direct completion indexes by activity. The information is always consistent with the project, and it is possible to make economic forecasts for the ob order management in real-time at each project change, both in the case of variations and changes made by the client. Even a small change within the model, such as the window’s frame dimensions or the thickness of a wall, is automatically updated in the metric and economic calculation.

The possibility provided by BIM to store any kind of information allows this tool to have enormous potential in the Facility Management (FM) phase, enclosed in BIM 6D. In order to guarantee the building maintenance, it is necessary to have a model that is faithful and corresponding to what has been realized, i.e. a “BIM-as built model” or a “Digital Twin” to use a definition that is used today. This model contains the exact information of the construction work realized, with all the details of every single element, component, and equipment installed. It represents a real archive from which it is possible to find any useful information for programming and coordinating all the maintenance activities during the whole life of any work designed in BIM.

The use of a BIM 6D model allows the immediate retrieval of all the design tables, all the products produced during the design and construction of the work, allows to improve the process and to avoid and significantly reduce waste in terms of time and costs. Specifically, the main benefits that can be obtained from the integration of FM with the BIM model are:

- optimization of maintenance programming procedures;
- reduction of maintenance time;
- reduction of errors in fault diagnosis;
- more excellent compatibility of the components to be replaced.

The introduction of BIM in Computer-Aided Facilities Management (CAFM)[57] systems allowed a sharp reduction in the time needed to enter the data required for FM, as they are already detailed in the single BIM model. The CAFM system, in fact, directly receives data via COBie[58] files from the BIM model thanks to the implementation of ad hoc interfaces in BIMoriented software. These systems, today, are also available web-based and, therefore, also usable through mobile devices, such as tablets or smartphones that allow constant monitoring of the work.

BIM 7D, finally, concerns aspects related to project sustainability. To frame the concept of sustainability in a new BIM perspective of innovation is not easy and there are not yet widely shared definitions in this regard. Eastman himself, in his last book, describes the dimensions of BIM only up to the fifth. However, it is possible to state that the adoption of the BIM methodology, which obliges planning and opens up the building organisation to simpler management, also makes it possible

57 CAFM systems correspond to a set of IT tools supporting Facility Management for the management of the work during its useful life. These systems were born from the integration of CAD tools (“Computer-Aided Design”) with the information databases necessary for the FM activity.

58 The Construction Operations Building information exchange (COBie) is an international standard format focused on project information rather than geometric data. COBie was developed in 2007 by Bill East, a member of the United States Army Corps of Engineers. The idea behind COBie is that key information is all collected in a single format and shared among stakeholders by providing a common structure for the exchange of information throughout the project lifecycle.

to make the analytical processes that are now involved in assessing the sustainability of the structure more efficient. BIM, therefore, thanks to a model rich in updated continuously information and increasingly faithful to reality, can be valuable support in simulations and analysis of energy performance and sustainability through data increasingly numerous and close to reality.

The dimensions described the deal with geometry, time, cost, management, and sustainability. Although there are already many of these aspects, they are not exhaustive, and some of them are missing. In the last months of the study activity concerning the dimensions of BIM, a new dimension (8D) corresponding to safety aspects has started to appear among the research results. It is, therefore, possible that soon this short description may no longer be complete and will need to be supplemented with new "D's".

Common Data Environment

Information and its exchange between all the people involved in the building process is the key to BIM innovation. While in the traditional process, information has always been provided in the form of drawings and paper documents, with digitization, the use of BIM, their collection, management, and sharing are entrusted to memory disks, servers, and the internet.

Maturity and BIM size increase corresponds to a relative growth in data and information contained in the BIM model. Although all this information is digitized, the high amount and inherent difficulties in a collaborative process among many technicians involved in a project require the definition of an organized data sharing space. To this end, the Common Data Environment (CDE) has been developed and models, specifications, and standards have been developed to create, acquire, and manage data in a more structured way. With direction and mentality change brought by BIM, the information exchange tools have revolutionized the relationships of the parties by considerably increasing the consistency and validity of the whole process.

The CDE, analysed by the first English technical standards BS 1192:2007[59] and PAS 1192-2:2013[60] and now also acquired in Italy with the new BIM standards[61] under the name of "ACDat", can be considered as the core of the BIM Level 2 process. It is a digital environment of organized collection and sharing of data related to work.

59 BS 1192:2007 Collaborative production of architectural, engineering and construction information - code of practice (+A2:2016). Status: Withdrawn.
60 PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling. Status: Withdrawn.
61 Italian BIM standard will be described in section 3.3.3.

The CDE is based on an IT infrastructure whose sharing is regulated by precise security systems for access, traceability, a historical succession of the changes made to the information content, attribution of responsibility for processing and protection of intellectual property.

As central repository consisting of one or more online storage, CDE is the primary means for sharing project work by providing a collaborative environment that can be widely customized according to business needs. The content is not limited to the information created in the BIM environment but includes documentation, graphic templates, and non-graphic resources. "CDE manager" is responsible for creating, setting up, and managing digital platforms and technological superstructures in which the BIM process takes place.

The use of the CDE improves the information collaboration between project members and ensures a substantial reduction of errors. Among the main advantages brought by the adoption of the CDE are:

- reduction of production time and costs, thanks to greater coordination and more accessible and more immediate sharing;
- possibility to create models originating from the combination of shared others;
- greater control over revision and data versions;
- maintaining ownership assignment to the originator, although all files are shared and reusable.

CDE's effectiveness is based on the data it contains and its organisation so that it can be easily found and reused at all stages of project development. The task of the CDE manager is to supervise that all designers use the CDE in a structured way, following a strict discipline made of agreed-upon approaches and procedures, such as universal coding or shared archiving protocols.

BS 1192[62] standardises and formalises for the first time the operating procedures of the CDE, regulating the organisation of the archives, the file nomenclatures, and the way they are exchanged (Figure 45). The information flow is schematized in distinct zones, differentiated according to the design phase, the completeness of the data contained and their originator. Data transition between the zones is regulated by controls and checks, which are configured as real "gates" for data validation: only when these are judged suitable by the supervisor responsible for the single-phase, can they be shared at a higher level. In each CDE environment, each document and the digital process is identified according to a revision and a suitability stage, defined as "suitability" in BS 1192:2007, which regulates its value.

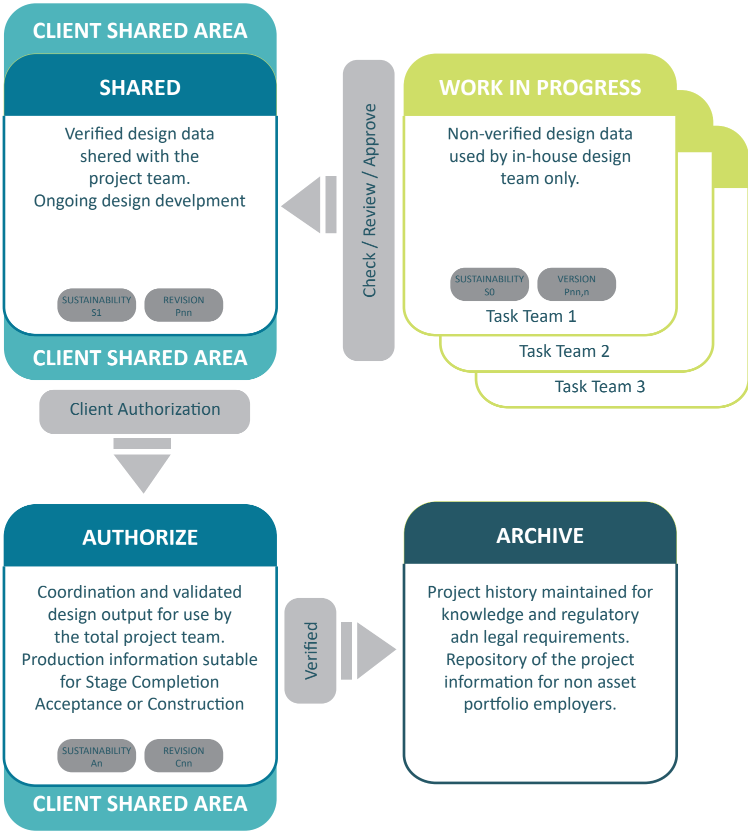


Figure 45 Outline presented in BS 1192 of the CDE areas and the approval steps between them (BS 1192).

The first area created in the design process is the Work In Progress Area (WIP), i.e. the area where individual technicians work independently, generating unverified data that is not yet ready to be shared at higher levels. In order to pass to the next zone, the information must pass through the first approval gate and pass certain checks, carried out by the project manager, including, for example, the suitability check of the model, the Standard Method and Procedure (SMP)[63] check or technical content check. Once reviewed and approved, the data may proceed to the next stage.

62 Although no longer in force, it is cited as the first historical reference for defining the CDE organisation.
63 Standard Method and Procedure (SMP) is defined in PAS 1192-2:2013 as a set of standard methods and procedures concerning the way information is named, expressed and referenced.

Shared Area is used to enclose both the information previously approved for sharing and the documents that require authorization from the client, contained in a sub-area called the "Client Shared Area". Once the client's authorization has been obtained, the information is validated again and then continued in the next step, the "Published Area". It contains the project documentation in the completed version, shared by the various design teams and approved by the client, and compliant with the EIR and the Plain Language Questions[64].

The last approval step leads to the area called "Archive", which is used to record the progress of the project at each "Milestone", creating a history of all the project transactions with related regulatory and legal requirements. The files contained in the Archive correspond to the actual status of the project and can no longer be revised or modified. Then, having established a procedure for the transfer of ownership of the information, the contractors will replace the original information entered by the designers with the actual information to constitute the final "as-built", so that the resulting graphical models can be used for manufacturing and installation.

The CDE organisation procedure presented here refers more directly to the case of new structures. However, as the standard itself suggests, it can also be used in the case of existing buildings, providing, upstream of all these steps, for a first phase dedicated to the archiving and organisation of the documentation collected relating to the state of affairs.

Common Language BIM has the potential to allow, by its very nature, collaboration and coordination of communication between the different actors involved in a building process. This intrinsic characteristic of BIM is repeated in any text and explanation on the subject, but it is not so simple to put into practice, and there are still many obstacles that slow down the achievement of full interoperability. The construction industry makes use of multiple software, for design and performance analysis, which uses a proprietary data representation system and has specific requirements that often differ or overlap. At the individual level, each software tool, while sharing the object orientation, could store object data in a proprietary format, thus hampering software interoperability and making the premise of collaboration, coordination, and communication underlying BIM unsustainable.

The need for standards for data exchange and the ensuing definition of sharing protocols is an even higher if not fundamental need for the new computerised design. It is for this reason that for about fifteen years now, various bodies from various countries around the world have been concentrating their efforts in the search for BIM

64 Employer Information Requirements (EIR) and the Plain Language Questions are contractual documents that are drafted and used in the initial phase of a project assignment to clarify the client's intentions.

solutions that improve the sharing of information at an international level between the various operators in the construction industry. Among the protagonists, who were the first to distinguish themselves in this field, we find the International Alliance for Interoperability (IAI), later renamed buildingSMART[65]. The association has made significant and necessary steps forward in this process:

- representation of the model, including graphical features properties and behaviour of the model components and contents;
- interoperability standards, including representation, and data interchange;
- agreement on common terminology on the creation of unique identifiers for products, components, and content;
- development of an open file format for data storage;
- creation of information sharing protocols;
- guaranteeing a certification service for compliant software applications.

In particular, buildingSMART has set the framework for technological development by promoting the interoperability process through the study of three components: terminology, process, and format for data exchange (Figure 46).

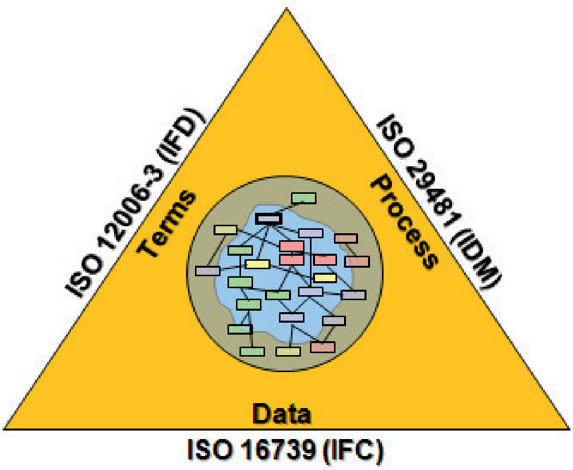


Figure 46 Exchange and share information and IFC, IFD, and IDM combined use (www.buildingsmart-tech.org).

65 buildingSMART Alliance is the board of the National Institute of Building Sciences that contributes to making the North American real estate sector more efficient, guiding the creation of tools and standards that allow virtual projects to be realized before they are physically built. It was created to guide technical, political, and financial support for the use of advanced digital technology in real estate, from conception, design to construction. The Alliance promotes the use of the Building Information Model by leading the development of open data standards to facilitate and improve facility and infrastructure information management.

Following Netherlands and Norway's efforts about the terminology implementation project, buildingSMART has created the IFD Library[66], an ontological library that establishes the criteria for the existence of entities from a formal language, spreading its consistent use internationally. Since BIM software applies an information reading scheme internally, it becomes essential to ensure mutual communication between the different tools and software in the sector. The implementations of vocabulary regarding construction terminology, thanks to univocal references for each object and product, is an indispensable tool to improve interoperability in the construction industry, which is now increasingly globalized, creating a bridge with existing databases.

The Information Delivery Manual (IDM) was created to standardize the design process. The manual is intended to specify what information should be exchanged in each project development scenario. Each user becomes aware of the information they need to provide in order to achieve a collaborative and productive exchange.

Finally, the Industry Foundation Class (IFC) has been defined and promoted for data exchange. It is an open data format that allows the global exchange of an information model about the construction life cycle, without loss or modification of data. The structure of an IFC is divided into four primary levels (Figure 47) that allow the encoding of standardized data in a logical way, related to identity and semantics, characteristics or attributes, relationships, objects, abstract concepts, processes, and people. All these data are generally encoded in the specific data language EXPRESS.

Work on the definition of the IFC began in 1994 and, despite several efforts to disseminate it, this free format, since any operator does not control it, still requires further studies to be carried out so that it can be used more and more effectively. Since its first publication in 1996, some updates to the IFC format have been published over the years. In 2016, the latest version called IFC 4 Add2 was released. In this version, there are 776 entities (object data), 413 property sets, and 130 defined data types. These numbers not only indicate the complexity of the IFC but also express the semantic richness of building information they can contain, increasingly responding to the needs of different applications, ranging from energy analysis to cost estimation to material monitoring and programming.

66 The International Framework for Dictionaries Library (IFD Library) was created to be an open and shared terminology library that supports object-oriented BIM information exchange. The IFD library offers the flexibility needed for the BIM model by allowing the link between it and the various databases with design and specific data. of the product. It is currently being developed by the International Alliance for Interoperability (IAI) buildingSMART. Thanks to a grant from the National Center for Energy Management and Building Technology, the Construction Specification Institute (CSI) is developing a terminology library and dictionary for North America.

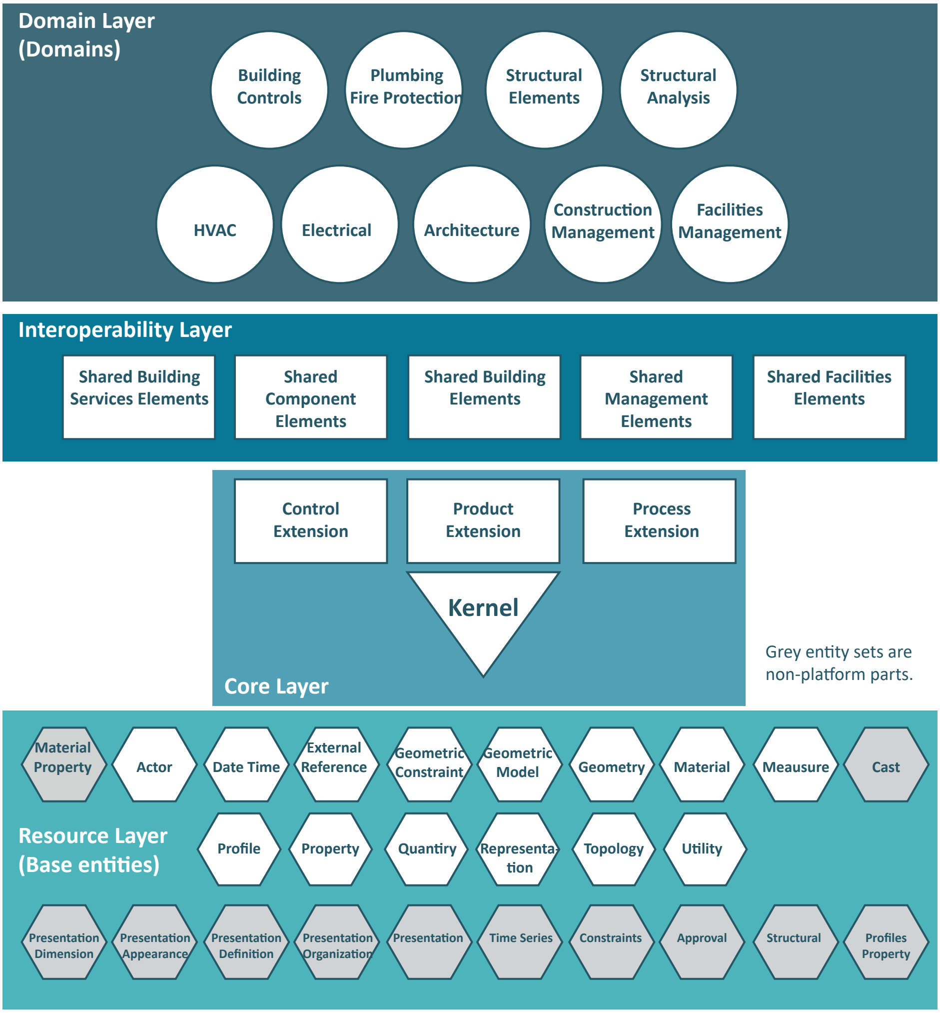


Figure 47 The system architecture of IFC subschemas. Each Resource and Core subschema has a structure of entities for defining models, specified at the Interoperability and Domain Layers. (Sacks et al. 2018)

3.3.2 BIM World Experiences

The adoption of the BIM methodology in design processes has followed different paths among the countries of the world, resulting in utterly different frameworks, although common bases have been laid to support the process of information exchange and to share on a global scale. Moreover, although the concepts behind BIM date back several decades ago, only recently, thanks to the debate on issues related to people and processes, it has gained popularity in the field and among researchers. This change has been taking place for less than ten years, and according to researchers, and professionals, the beginning of the so-called "BIM era" is between 2005 and 2008[67]. In recent years, the combination of technology, people and processes allowed by BIM has taken hold and increasingly intense activity in the sector and academic communities has developed.

Today, although the concept of BIM is widespread throughout the world, the situation regarding the degree of BIM implementation, standards, and initiatives are heterogeneous. Figure 48 shows the global picture map. It is evident that many countries are involved in this issue, but not all countries have reached the same results at the same time, having to start from experimental projects and developing their expertise directly in the field.

Governments around the world increasingly recognise the effects that can be achieved with this change. Learning from major countries, governments embarking on the transformation path are convinced that the strategic use of BIM can support a leaner and more innovative construction sector, thereby addressing the decline in productivity prevalent in the sector. The differences are also widely found at the national level, depending on the company and its willingness to spend funds on an upgrade that may not even return the expected results, since for efficient use of BIM all parties involved must have the same system, involving the supply chain from designers to suppliers.

Currently, the governments of the UK, Hong Kong, and South Korea have developed many BIM initiatives in recent years, as have the Scandinavian countries of Norway, Denmark, and Finland, and the USA, who have been working with BIM for over a decade. Analysis by the Irish Construction IT Alliance (CitA)[68] shows that more than 50% of the 27 countries have BIM regulatory requirements in place or are planning to implement them shortly.

67 Sacks, R., Barak, R., 2010. Teaching Building Information Modeling as an Integral Part of Freshman Year Civil Engineering Education. J. Prof. Issues Eng. Educ. Pract. 136, 30–38. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000003 Edgar, A., 2007. W15: Introduction to BIM: People, Processes and Tools. NIBS.

In the USA, the National Institute of Building Sciences (NIBS) began working on BIM through the Facility Information Council in 1998. In 2007, the National BIM Standard (NBIMS)-US Project Committee[69] published the National BIM Standard, version 3 of which is now available. This is probably the first reported intervention, similar to the development of a computer-aided design (CAD) standard decided by a government at the national level. At about the same time, the US General Services Administration (GSA) also launched its national 3D-4D BIM Program in 2003. The adoption of BIM in North America increased dramatically from 28% to 71% between 2007 and 2012, where the adoption by contractors now slightly exceeds that of architects[70].

In the UK, BIM developed very slowly until the UK Government's BIM Task Group published a BIM Policy in May 2011. The UK Government has made the use of BIM mandatory for every new public sector project since April 2016. At the same time, as the initiative to achieve a Level 2 BIM, the UK has implemented a suite of related facilities and guidelines that have established themselves as guidelines in many other countries. This includes a set of publicly available specifications (PAS) and British Standards (BS), which offer the best of practice in information management for capital/delivery and operational phase of construction projects using BIM. The UK Government most recently undertook an ambitious programme to achieve BIM Level 3 and is now recognised as a world leader in the adoption of BIM with widespread use in recent years.

In other parts of the world, even in developing countries, there are similar activities: for example, Oceania is in fourth place, behind North America, Europe, and Asia, in terms of depth and level of implementation and years of use of BIM[71]. McGraw Hill's 2014 report[72] showed the commercial value of BIM in Australia and New Zealand, pointing out that although BIM is relatively new in these countries, its value has been widely acknowledged, with 74% of companies surveyed saying they will commit to BIM on more than 30% of their projects by 2016. The business value of BIM in China was also highlighted, with a 200% increase in architects at a BIM implementation level, while a second roadmap for BIM in Singapore was made more productive within the public sector.

68 McAuley, B., Hore, A., West, R., 2017. BICP Global BIM Study - Lessons for Ireland's BIM Programme Published by Construction IT Alliance (CitA) Limited. http://doi.org/10.21427/D7M049
69 This is a specific committee of the buildingSMART alliance of NIBS.
70 McGraw Hill Construction, 2014. The Business Value of BIM for Construction in Global Markets, McGraw Hill Construction, Bedford MA, United States.
71 Jung, W., Lee, G., 2015. The Status of BIM Adoption on Six Continents. International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering Vol:9, No:5
72 McGraw Hill Construction, 2014. *Ibid.*

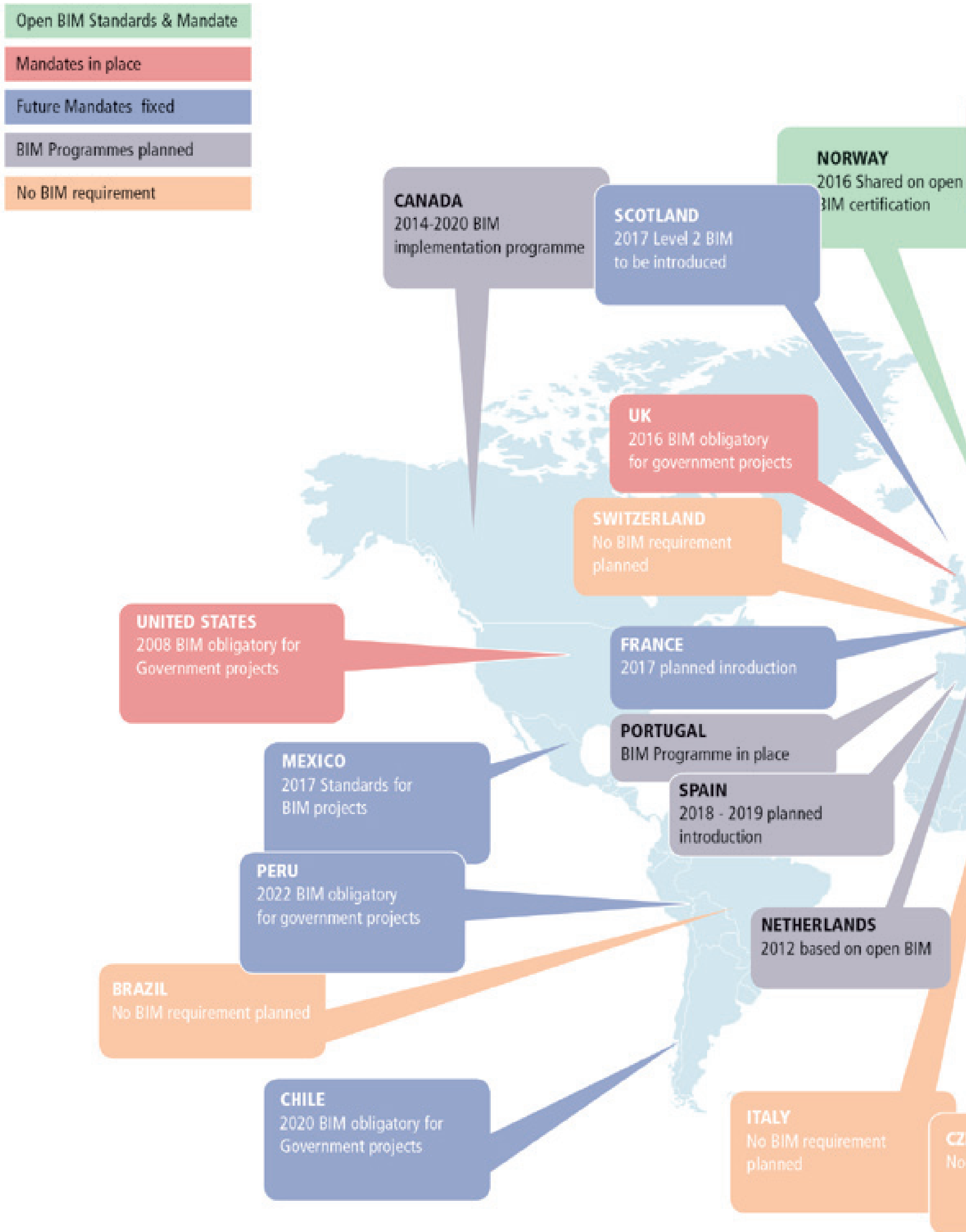
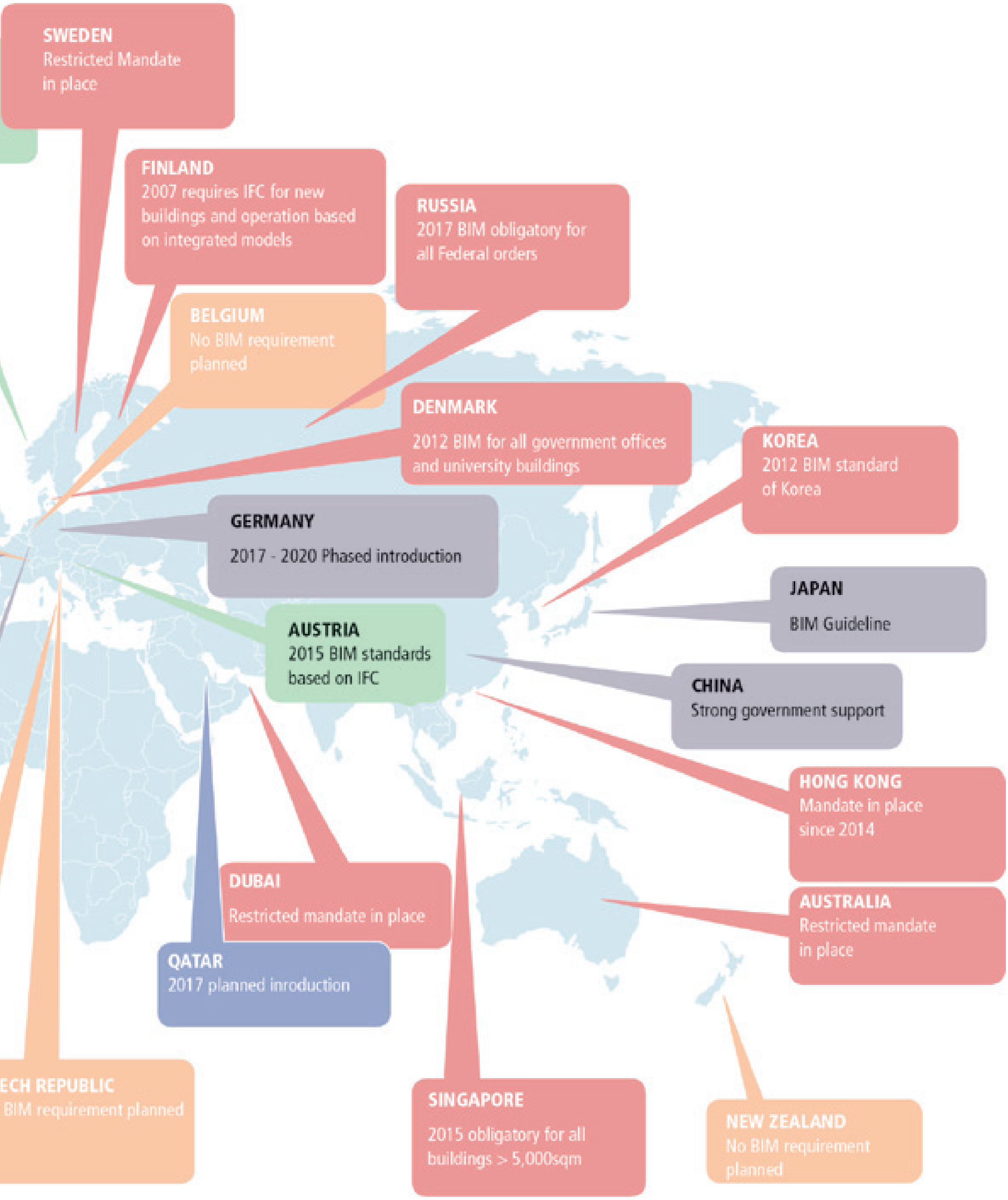

Open BIM Standards & Mandate
Mandates in place
Future Mandates fixed
BIM Programmes planned
No BIM requirement
NORWAY
2016 Shared on open BIM certification
CANADA
2014-2020 BIM implementation programme
SCOTLAND
2017 Level 2 BIM to be introduced
UK
2016 BIM obligatory for government projects
SWITZERLAND
No BIM requirement planned
UNITED STATES
2008 BIM obligatory for Government projects
FRANCE
2017 planned inroduction
PORTUGAL
BIM Programme in place
MEXICO
2017 Standards for BIM projects
SPAIN
2018 - 2019 planned introduction
PERU
2022 BIM obligatory for government projects
NETHERLANDS
2012 based on open BIM
BRAZIL
No BIM requirement planned
CHILE
2020 BIM obligatory for Government projects
ITALY
No BIM requirement planned

Figure 48 Global map of BIM adoption at the national level (McAuley 2017).



In the European context, after the EU Procurement Directive 2013, which showed its support for BIM through its ratification by the European Union Parliament, many countries have demonstrated a particular enthusiasm and interest in BIM.

In 2015 a European working group on BIM called the EU BIM Task Group[73], was set up, and the European Commission assigned it the task of providing a common approach to the European network for a BIM use alignment. The Task Group aims to support public procurers, policymakers, and public property owners by producing a manual containing a guide to BIM. The manual will include procurement measures, technical considerations, cultural and skills development, and overall benefits for public procurers in the use of BIM. The following European Member States are currently members of the group: Austria, Belgium, Czech Republic, Germany, Denmark, Estonia, Finland, France, Iceland, Ireland, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom.

In Italy, the European Directive 2014/24/EU on public procurement has activated the Italian legislative machine on BIM and the introduction of laws requiring its use from 2019, for now only in the public procurements. As already mentioned, the Directive has been implemented in Italy with "Decreto Legislativo n. 50/2016" on Public Contracts. Article 23, paragraph 1, letter h) states that design in the field of public works is intended to ensure the rationalization of design activities and related checks through the increasing use of specific electronic methods and tools such as modeling for construction and infrastructure. Article 23, paragraph 13 instead, with the following sentence, describes the characteristics that these tools must possess and the need for trained personnel: these tools use interoperable platforms through non-proprietary open formats in order not to restrict competition between technology providers and the involvement of design specifications among designers. Contractors with appropriately trained personnel may only require the use of electronic methods and tools. The "Decreto Ministeriale 560/2017"published by the Ministry of Infrastructure and Transport sets the details for BIM implementation, methods, and timing for the progressive and mandatory introduction in public procurement (Figure 49).

73 Further information available on www.eubim.eu
74 ASSOBIM, founded in October 2017, is an Italian association that aims to give representativeness to the "technological" supply chain of Building Information Modeling. AssoBIM brings together the companies operating in the supply chain: from software houses to BIM service providers, from large contractors to engineering companies, also involving manufacturers of materials and components to be the reference association in the dialogue with institutions.
75 AssoBIM Report 2019. Available on www.assobim.it/bim-report-2019/

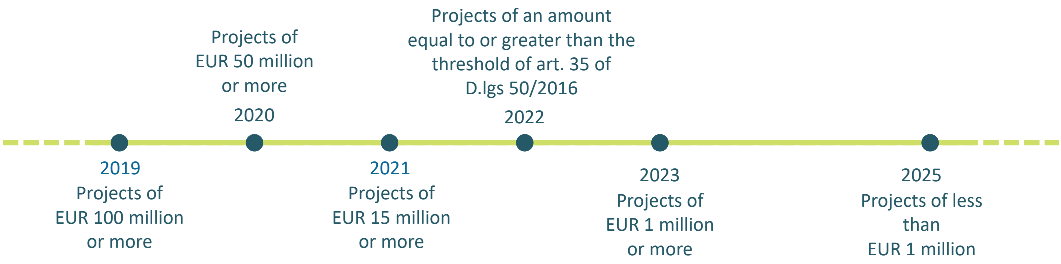


Figure 49 BIM implementation timeline in Italy in public procurement.

AssoBIM[74] published in July 2019 the results of the market survey on the BIM implementation in Italy[75]. The survey was carried out on a sample of over 600 operators (design firms, engineering companies, construction and maintenance companies, public and private clients, and manufacturers of materials and components), which faithfully reflects the scale of the Italian professional realities.

The 62% of participants are design firms, with an average number of collaborators below ten in 76% of the cases and a turnover below one million euro in 75% of the cases. Their answers show a strongly growing situation (Figure 50): more than half of the sample knows and uses the BIM methodology, while a further 40% know it but do not use it or make partial use of it and only a marginal number of operators (below 10%) are not aware of it. Another interesting aspect that emerged is the year in which BIM was introduced in the company (Figure 51): since 2012, it is possible to detect a constant growth that peaked in 2018 when 17% of the sample introduced the digital methodology permanently in the company. Among those who do not yet use BIM, about 11% expect to introduce it in the company within a year, and almost 20% will do it in the next three years. The answers to two additional questions help to define the contours of this trend better: almost half of the sample stated that they have adopted BIM in their projects extensively (22.94%) or partially (24.21%) (Figure 52), but almost 60% of respondents have used it in less than 25% of the projects, while about 14% have applied it to all the projects carried out (Figure 53).

From other answers shown in the report, it emerges that 70% of the sample is very or quite convinced that BIM can contribute actively, up to one third less, to the reduction of the initial construction cost and of the costs related to the entire life cycle of the building, as well as to the reduction, up to 50% less, of the overall construction time, from the start to the completion of the works. More significant reservations, on the other hand, were expressed about the contribution made by the adoption of BIM to the reduction of the environmental impact of construction activities and the trade imbalances between imports and exports of building components and materials, aspects on which two-thirds of the sample expressed doubts. In conclusion, however, taking into account the low speed of digital adaptation in Italy, the results are promising. However, a further boost to the adoption of BIM is expected soon, given the recent change in the regulatory framework on the mandatory nature of BIM for public works.

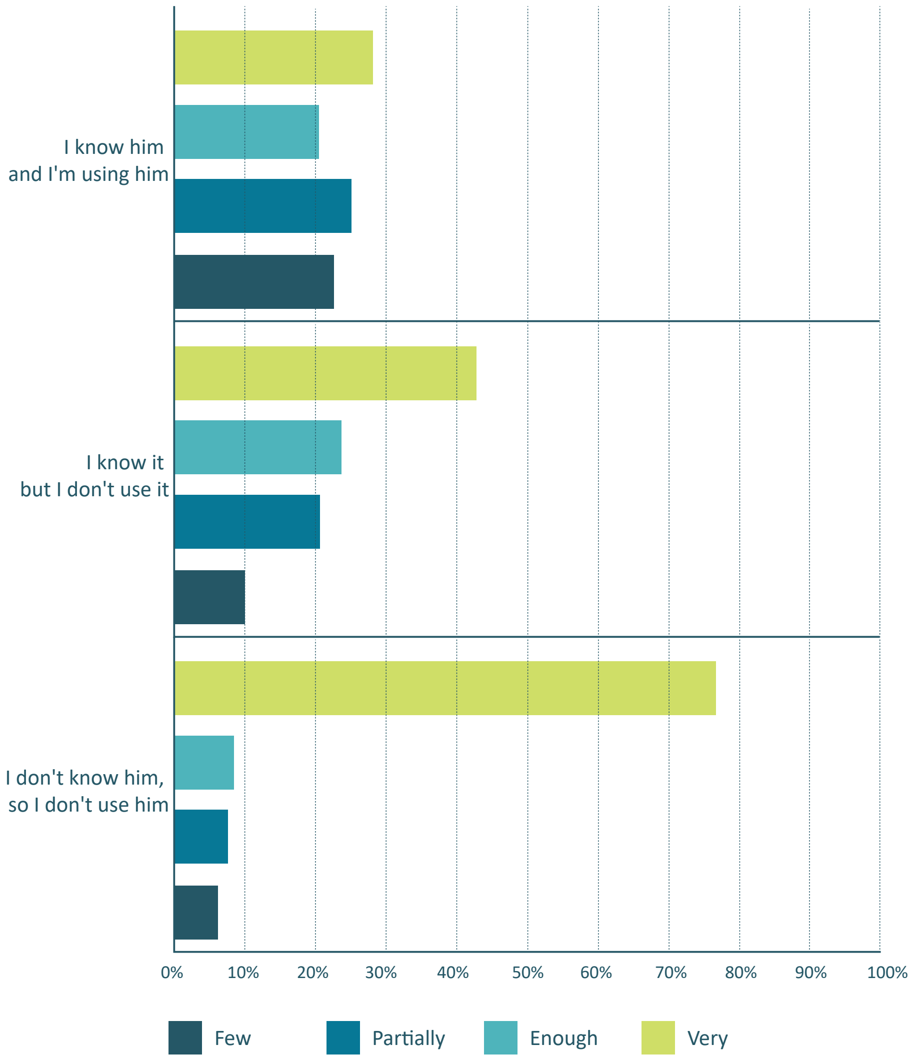


Figure 50 Degree of knowledge and use of BIM (AssoBIM 2019).

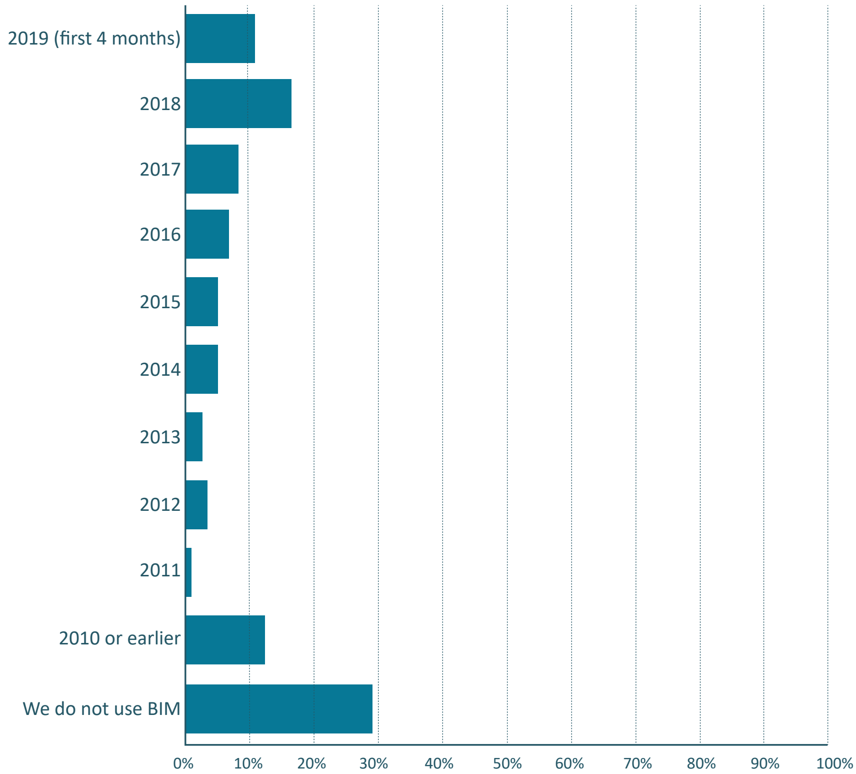


Figure 51 Year of BIM implementation in the company (AssoBIM 2019).

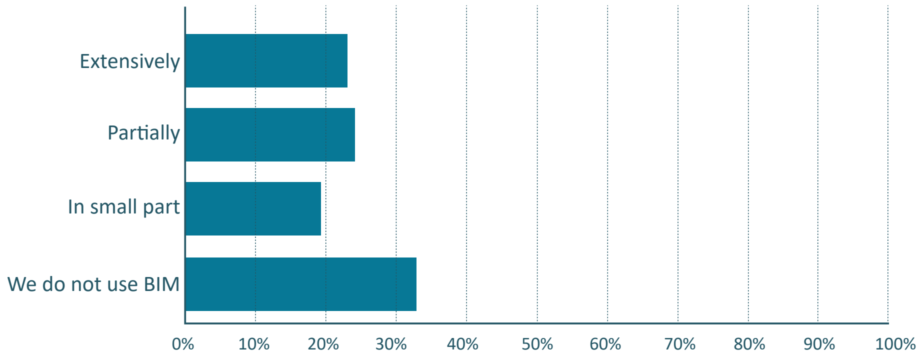


Figure 52 Percentage of BIM adoption in company projects (AssoBIM 2019).

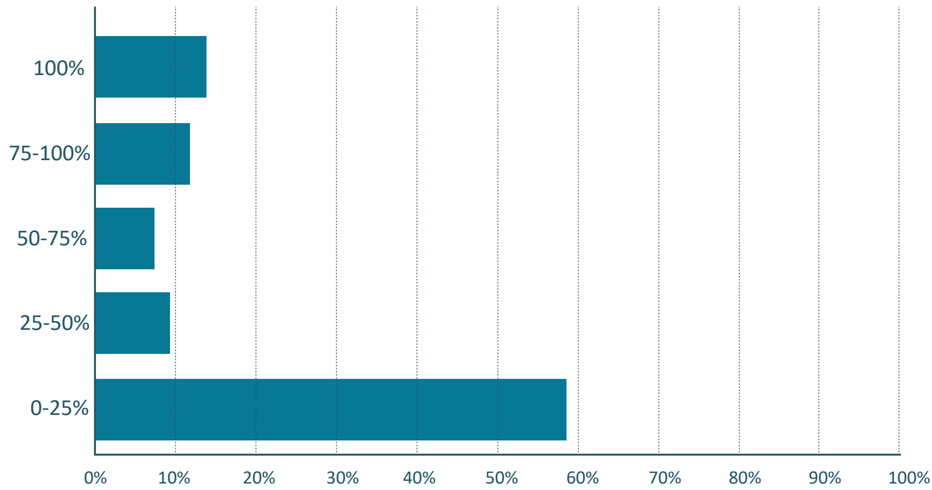


Figure 53 Percentage of use of BIM in projects carried out in the last twelve months (AssoBIM 2019).

In the following section, the global standards issued by the International Organization for Standardization (ISO) and those specific to the Italian context published by the Italian National Unification Body (UNI) will be discussed in more detail.

3.3.3 BIM Standards Framework

The origins of "Building Information Modelling" can be found already in the seventies and its first applications in the eighties. Nevertheless, we must look to the end of last year, 2018, to find the first global standards issued by the International Organization for Standardization (ISO). It is ISO 19650:2018 - Organization and digitization of information about buildings and civil engineering works, including Building Information Modelling, which has reorganized all the standards implemented at national level by providing a unique definition at international level for the exchange of data and establishing standard protocols for sharing information between the various operators in the construction industry.

It is thus clear that the introduction of the BIM concept to the goal of global standards has been a long path. Several bodies all over the world have contributed to defining standards and protocols in the BIM field.

One of the first players to start defining common standards was the International Alliance for Interoperability (IAI), renamed in 2007 as buildingSMART, as already mentioned. buildingSMART is credited, not only with having developed IFC format but also with having laid the foundations for interoperability through the study of common terminologies and processes. buildingSMART is still one of the reference bodies for BIM and collaborates in the drafting of ISO standards by participating in the technical working group ISO/TC 59/SC 13 - Organization and digitization of information about buildings and civil engineering works, including BIM.

In this technical committee, we also find the OGC - Open Geospatial Consortium, Inc. To this date, 31 countries join it, which: Great Britain, Italy, Germany, France, Spain, Portugal, USA, Australia, Austria, Switzerland, Belgium, Brazil, Canada, China, Chile, Kazakhstan, Malaysia, Netherlands, Peru, Czech Republic, Turkey, Singapore, Slovenia, Russia, Hungary, Romania, Japan, Denmark, Finland, Sweden, and Norway.

In the long process of developing standards for BIM, another significant contribution is made by the British Standards Institution (BSI). The ISO 19650:2018[76] is, in fact, inspired by the English standard PAS 1192: it has acquired its supporting structure and has also introduced requirements that will revolutionise the consolidated procedural and contractual structure of many of the participating countries.

ISO 19650:2018 ISO 19650:2018 has been designed for the entire life cycle of any built asset, including strategic planning, initial design, engineering, development, documentation and construction, day-to-day operation, maintenance, refurbishment, repair, and end-of-life. This document can be adapted to assets or projects of any scale and complexity, so as not to hamper the flexibility and versatility that characterize the broad range of potential procurement strategies and to address the cost of implementing this document. At present, the standard consists of two parts that address different aspects.

The first part outlines the concepts and principles for information management at a stage of maturity described as "Building Information Modelling (BIM) according to the ISO 19650 series". The document also provides recommendations for a framework to manage information, including exchanging, recording, versioning, and organizing for all actors. The ISO 19650-1:2018 frames the information flow of the building process within the broader horizon of Project Management. The document is primarily intended for use by the following:

- those involved in the management or production of information during the delivery phase of assets;

76 ISO 19650-1:2018 - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling.

- those involved in the definition and procurement of construction projects;
- those involved in the specification of appointments and facilitation of collaborative working;
- those involved in the design, construction, operation, maintenance and decommissioning of assets;
- those responsible for the realization of value for their organization from their asset base.

The diagram in Figure 54 summarises the relations between them: the already existing and commonly adopted approaches the management of assets and projects and for organisational management and the new information management.

The Information Management is divided into two parts: Delivery Phase (PIM - project information model) and Operational Phase (AIM- asset information model). Three passing moments are also identified:

- A start of delivery phase – transfer of relevant information from AIM to PIM;
- B progressive development of the design intent model into the virtual construction model;
- C end of delivery phase – transfer of relevant information from PIM to AIM.

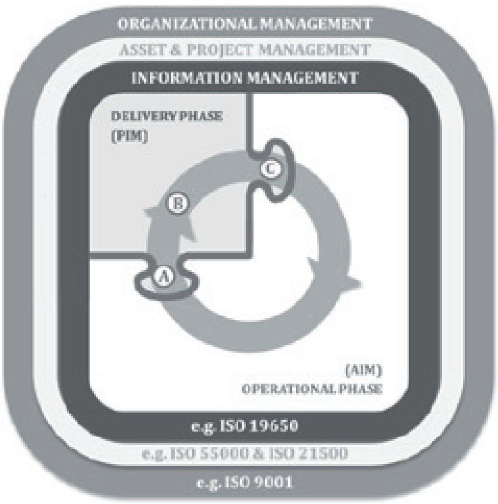


Figure 54 Generic project and life cycle asset information management (ISO 19650:2018).

From the point of view more appropriately of the life cycle of the building, the entire information flow is summerized in Figure 55. It makes it possible to highlight the intermediate moments of evaluation, verification, and approval, in which the customer is also called to express his opinion about the satisfaction of the initially expressed design requirements.

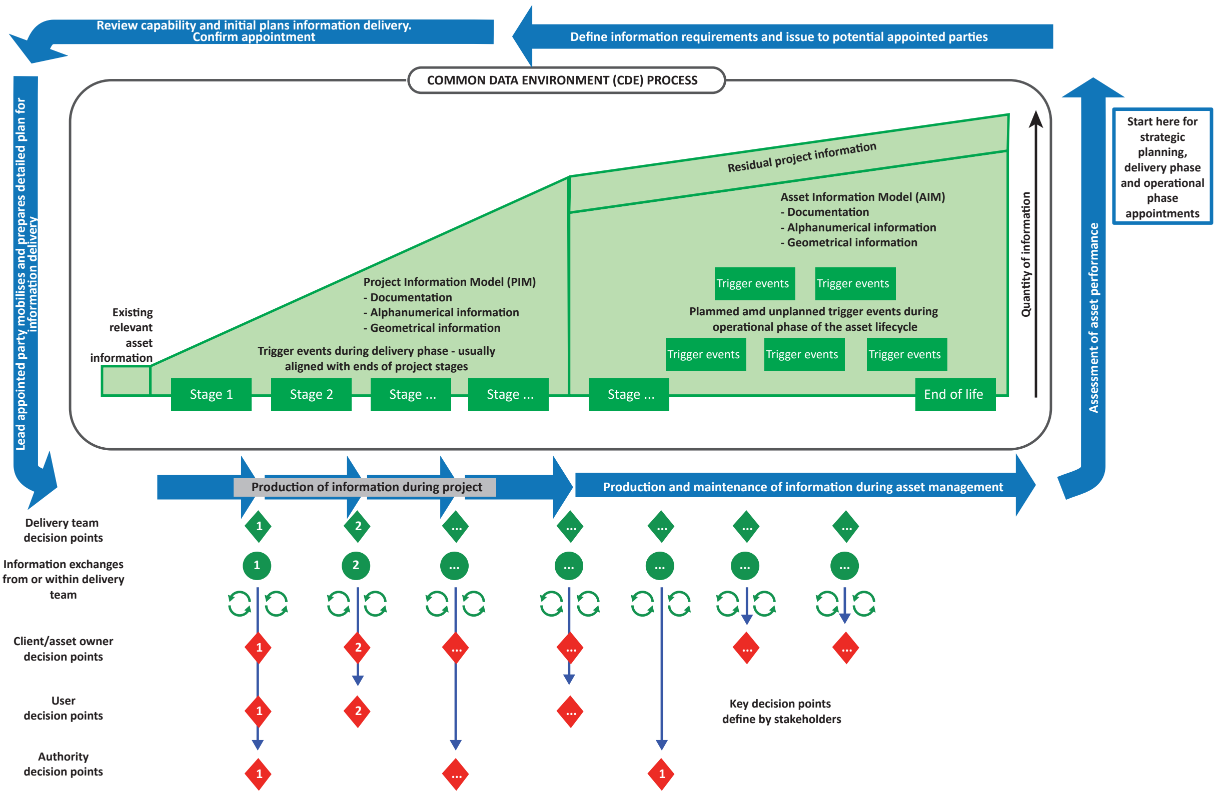
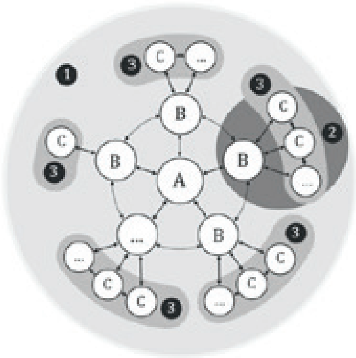


Figure 55 Overview and illustration of the information management process (ISO 19650:2018).

The second part, ISO 19650-2:2018, goes more specifically into the delivery phase of the activities. This document specifies requirements for information management, in the form of a management process, within the context of the delivery phase of assets and the exchanges of information within it, using building information modeling. This part deals first of all with the protagonists, specifying in their placement within the process chain and their roles and functions (Figure 56). The schema shows the interfaces between parties and teams in terms of information management and should not be seen as an identification of contractual relationships.



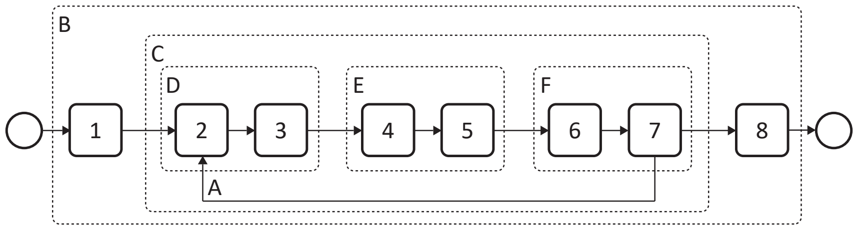
KEY

A appointing party
B lead appointed party
C appointed party
variable amount

1 project team
2 illustration of a delivery team
3 task team(s)

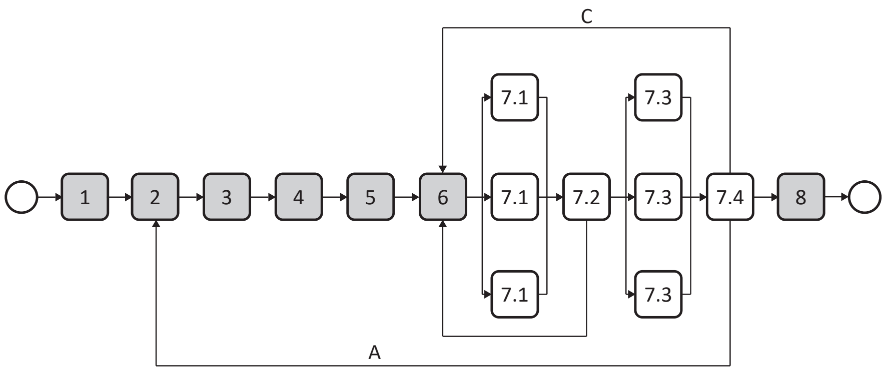
Figure 56 Interfaces between parties and teams for information management (ISO 19650:2018).

Then, the document enters into a specific description of the various phases of the information process. It is also possible to find all the details of the general workflow and its structure, from the methodological point of view and the objectives of every single step (Figure 57). Each phase is also then dealt with in detail with specific schemes. For example, all the sub-activities related to the 7 – Information Model Delivery are specified in Figure 58.



1	assessment and need	A	information model progressed by subquent delivery team(s) for each appointment
2	invitation to tender	B	activities undertaken per project
3	tender response	C	activities undertaken per appointment
4	appointment	D	activities undertaken during the procurement stage (of each appointment)
5	mobilization	E	activities undertaken during the information planning stage (of each appointment)
6	collaborative production of information	F	activities undertaken during the information production stage (of each appointment)
7	information model delivery		
8	project close-out (end of delvery phase)		

Figure 57 Information management process during the delivery phase of assets (ISO 19650:2018).



7.1 submit information model for lead appointed party authorization
7.2 review and authorize the infromation model
7.3 submit information model for appointing party acceptance
7.4 review and accept the information model
A information model progressed by subsequent delivery team(s) for each appointment
B information model rejected by lead appointed party
C information model rejected by appointing party

Figure 58 information management process: details of information modeling delivery step (ISO 19650:2018).

Others Global Standards The ISO 19650:2018 standard is the crucial reference for BIM, but there are also others currently in force that deal with specific aspects of the subject. Most of them are always developed by the technical committee ISO/TC 59/SC 13.

Among the most recent, there is ISO 16739-1:2018[77]. The standard, as the title suggests, is specific to the IFC: in it, we can find the definition, the data scheme, and the structure of the file format for the exchange of information.

The international dictionary, called IFD - International Framework for Dictionaries, is found in the ISO 12006-3:2007[78]. The standard contains information, such as definitions of objects, their properties, etc., to be used in order to allow standard understanding information flows with less difficulty. In the second part, instead,

77 ISO 16739-1:2018 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema.
78 ISO 12006-3:2007 - Building construction - Organization of information about construction works - Part 3: Framework for object-oriented information.

the ISO 12006-2:2015[79], we find a framework for the development of classification systems of the built environment. It identifies a set of recommended classification table titles for a range of information object classes according to particular views, e.g. by form or function, supported by definitions. It shows how the object classes classified in each table are related as a series of systems and sub-systems, e.g. in a building information model.

A methodology and format to describe the "acts of coordination" between the actors in a construction project during all phases of the life cycle are provided by ISO 29481[80]. The standard consists of two parts, the first published in 2016 and the second in 2012. ISO 29481 has been developed to facilitate interoperability between the software applications used during all phases of the construction works' life cycle and of promoting digital collaboration between the actors involved, through the definition of a methodology and a format, and providing the analysis of the interactions' framework.

ISO 16757[81] aims to provide a reference for electronic product catalogues data structures. It could be useful to automatically transmit construction services product data to construction services software models. It also consists of two parts: the first, published in 2015, deals with concepts, architecture, and the model, while the second, issued in 2016, deals with geometry.

ISO 16354:2013[82] provides guidelines for creating new object libraries and updating existing ones to standardize them and provide developers with clear indications.

Finally, the ISO/TS 12911:2012[83] establishes a reference for the commissioning of the BIM, i.e. the project management process that ascertains and documents that the performance of the building and systems meet defined objectives and criteria.

Italian Standards Framework

The ISO 19650 standard, developed within the framework of the agreement between ISO and CEN known as the "Vienna Agreement"[84], was automatically adopted by the CEN - European Committee for Standardisation as ISO EN 19650. Following this, all member states were called upon to intervene on any existing national standards to adapt them to this new reference, if in conflict with it, or supplement them if not complete.

79 ISO 12006-2:2015 - Building construction - Organization of information about construction works - Part 2: Framework for classification.
80 ISO 29481 - Building information models - Information delivery manual.
81 ISO 16757- Data structures for electronic product catalogues for building services.
82 ISO 16354:2013 - Guidelines for knowledge libraries and object libraries.
83 ISO/TS 12911:2012 - Framework for building information modelling (BIM) guidance.

In 2019, the Italian National Unification Body (UNI) published the two parts of ISO, UNI EN ISO 19650-1:2019 and UNI EN ISO 19650-2:2019. At the same time, UNI started work to revise the already published parts of UNI 11337 and to develop future references coordinated with the new indications present in the international ones.

UNI 11337[85], entitled "Construction and civil engineering works - Digital management of construction information processes", is the Italian reference standard for BIM, applicable to any type of asset and process. This standard was published before ISO 19650 but now is withdrawn in order to be completely redesigned. Today it is being reconsidered by ten parts. Five of them have already been published (1-4-5-6-7), one still in force in the old structure and will be updated (3), and the rest are under development (2-8-9-10) (Table 1).

These new standards UNI deal with and will deal with various aspects of BIM related to the development of information models, processes, objects, and information flows in digitized processes. A summary of the parts already published in the new structure of UNI 11337 is given below.

Table 1 Framework updated in October 2019 on published parts of UNI 11337.

Part	Standard Number	Title
1	UNI 11337-1:2017	Models, documents and informative objects for products and processes
2		Criteria for the designation and classification of models, products and processes
3		Models for collecting, organising and storing technical information for construction products (digital information sheets for products and processes)
4	UNI 11337-4:2017	Evolution and development of information within models, documents and objects
5	UNI 11337-5:2017	Informative flows in the digital processes
6	UNI 11337-6:2017	Guidance to redaction the informative specific information
7	UNI 11337-7:2018	Knowledge, skill and competence requirements of building information modelling profiles
8		Integrated Information Management processes and of Decisions
9		Information management during operation (Due Diligence, Collaborative Platform and Building File)
10		Organization of the figures involved in the management and information modelling

84 The Vienna Agreement on Technical Cooperation was signed in 1991 between CEN (European Committee for Standardisation) and ISO (International Organisation for Standardisation). It was drawn up to prevent duplication of effort and reduce the time taken to prepare standards. Consequently, the draft new standards are planned jointly by CEN and ISO and, once completed, adopted by both bodies.
85 UNI 11337 - Construction and civil engineering works - Digital management of construction information processes.

UNI 11337–1:2017 The first part of the 11337[86] covers the general aspects of digital management of the information process in the construction sector. Three fundamental aspects of the process are highlighted and then they are also the subject of in-depth analysis:

- the structure of information vehicles;
- the structure of the information process;
- the structure of the product information.

This standard can be applicable to any type of product (resulting) in the sector, whether it is a building or an infrastructure, and to any type of process: conception, production, or operation. It can be applied to new constructions, conservation and/or requalification of the environment or the built heritage.

The first challenge when writing a law is represented by terminology since the terms used must be clear, understandable, and shared. This is why in this first part of the standard, it possible to find a paragraph named "terms and definitions". It is divided into five parts:

- terms related to information content;
- terms related to information environments;
- terms relating to the product information structure;
- terms relating to the information structure of the space;
- terms related to the information structure of the process.

Subsequently, the standard deepens the aspects related to the structure of information vehicles in the paragraph called "documents and information models". In the construction sector, the transfer of knowledge of negotiation between the interested parties of any process takes place through data, information, and informative contents.

In the digitalization process of the construction sector, the production, management, storage, and transfer of data and information content, takes place through the use of computerized systems. Information contents are composed of data that can be:

- electronically structured or unstructured: reworkable or not reworkable; related or unrelated.
- fixed on digital or non-digital support: written in a proprietary format; written in an open format.

86 UNI 11337-1:2017 - Building and civil engineering works - Digital management of the informative processes - Part 1: Models, documents and informative objects for products and processes.

Information and knowledge in the construction sector can be transmitted in two ways: representation and virtualization. Operationally they can, in turn, be configured as graphics, document, or multimedia methods (Figure 59).

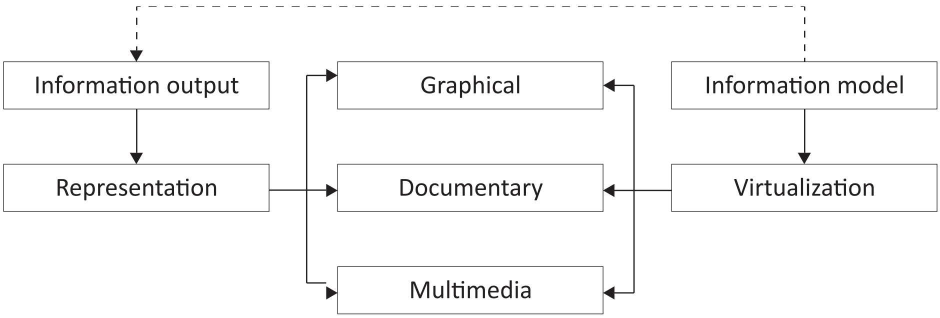


Figure 59 Schematic representation of information flows (UNI 11337-1:2017)

The standard then defines Italian digital maturity levels of the digital process different from those defined at the global level, which has been previously described. They are defined according to the different degrees of the evolution of the information transfer method.

Five degrees of maturity are identified:

- **level 0: non-digital**
  In all disciplinary areas (social, environmental, technical, economic, and legal), information sharing is carried out through non-digital works on a predominantly paper-based medium, although such works may derive from digital works.
- **level 1: base**
  In all disciplinary areas (social, environmental, technical, economic, and legal), information sharing is carried out through both digital and non-digital documents, but the necessary support remains the paper support.
- **level 2: elementary**
  Information sharing for the technical areas usually takes place through the use of graphic models. While for all the other disciplinary fields, the transfer takes place through digital elaborations. Contractually, the most commonly used medium remains on paper, but this time it is also accompanied by the digital one as regards the graphic models.

- **level 3: advanced**
  The exchange of information takes place through graphic models and digital processes (graphic, documentary, or multimedia). It is also possible to use a particular digital product or process information sheets for this purpose[87].
- **level 4: optimal**
  The information exchange, in all disciplinary areas, is carried out by using information models.

Sometimes, and only for specific needs, these models can be added by digital documents. Contractually, the various models are archived as defined in the various phases of the evolutionary process of the project.

In the last part, there are two paragraphs dedicated to the informative structure of the process and the product. Relevant is the schema (Figure 60) on the informative structure of the construction process. It represents a structured sequence of stages, in turn, divided into phases, which concern the production and management of contents.

In the upper part of the diagram, it is possible to see that the stages of the information process are divided into parts: the project phase and the work phase. This approach is similar to the one we already found in ISO 19650, which were introduced the PIM – Project Information Model and AIM – Asset Information Model.

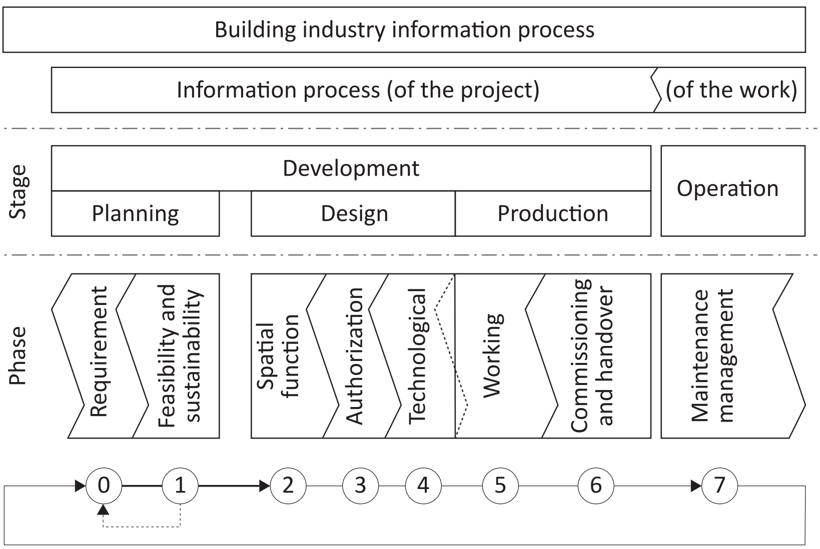


Figure 60 Informative structure of the construction process (UNI 11337-1:2017).

87 The structure of these sheets is developed by UNI 11337- 3 that is now under revision.

UNI 11337-4:2017 The fourth part of the 11337[88] is focused on qualitative and quantitative aspects of the digitalized management of the information process in the construction sector, in support of the decision-making process, with the aims of:

- specify the objectives of each phase of a process, introduced by 11337-1;
- define a common scale of development level of the objects related to the models;
- define a shared scale of the processing and approval phase of the contents.

First, we find the specification of the objectives of the stages of each process. The information evolution of the models is, therefore, functional to the achievement of these objectives. Therefore, the quality and quantity of information contained in the models must also be correlated to these goals. Finally, the use of the model makes it necessary to specify the Level of Development (LOD)[89] each object contained in it. The LOD of the objects must be adequate to allow the extraction of the required documents.

In particular, the standard provides for the following levels of development (Figure 61):

- LOD A: symbolic object;
- LOD B: generic object;
- LOD C: defined object;
- LOD D: detailed object;
- LOD E: specific object;
- LOD F: executed object;
- LOD G: updated object.

Figure 61 Example of window LOD (UNI 11337-4:2017).

88 UNI 11337-4:2017 - Building and civil engineering works - Digital management of the informative processes - Part 4: Evolution and development of information within models, documents and objects.
89 LOD is the English acronym but is also used in Italy.

UNI 11337-5:2017 The fifth part[90] defines the roles, rules, and flows necessary for the production, management, and transmission of information and their connection and interaction in the digitized construction processes. For this reason, it is possible to find some "new"[91] terms and their definition in the document. In particular, we find the following definition, of which the English version is also shown in brackets:

- Information coordinator (or BIM Coordinator): whose responsibilities are related to the management of the application of the information rules of the construction process;
- Information manager (or BIM Manager): guiding figure of the entire information process, oriented to the management of the information rules of the process;
- Information modeler (or BIM specialist): dedicated to the creation of models, is the one who uses the information rules of the construction process;
- Informative Specifications (or Employers Information Requirement): new contractual document with which the client defines the needs and information requirements that must be met by the contractors, as competitors or contractors;
- offer for Information Management (or BIM Execution Plan pre-contract award): it is a document in which the entrant to the contract, expresses and specifies its method of information management of the process, in response to requests from the client formulated in the Information Specifications mentioned above;
- Information Management Plan (or BIM Execution Plan - BEP): the final and operational explanation of the information management mode of the process prepared by the contractor (winner of the tender);
- analysis of inconsistencies (or Code Checking): it is the action of assessing possible information inconsistencies of the models (and related components), processed concerning rules and regulations;
- analysis of geometric interferences (or Clash Detection): it is the action of possible geometric interferences between objects, models, and processes.

The introduction of all these definitions, combined with those of the "data-sharing environment" (or Common Data Environment - CDE) and the "document sharing archive" (or Data Room), allows to have an almost complete Italian standard of all the terminologies defined in the English standards from which those have been developed the International ones.

90 UNI 11337-5:2017 - Building and civil engineering works - Digital management of the informative processes - Part 5: Informative flows in the digital processes.
91 These terms are new in the Italian context but known in the rest of the world because the English standards already define them.

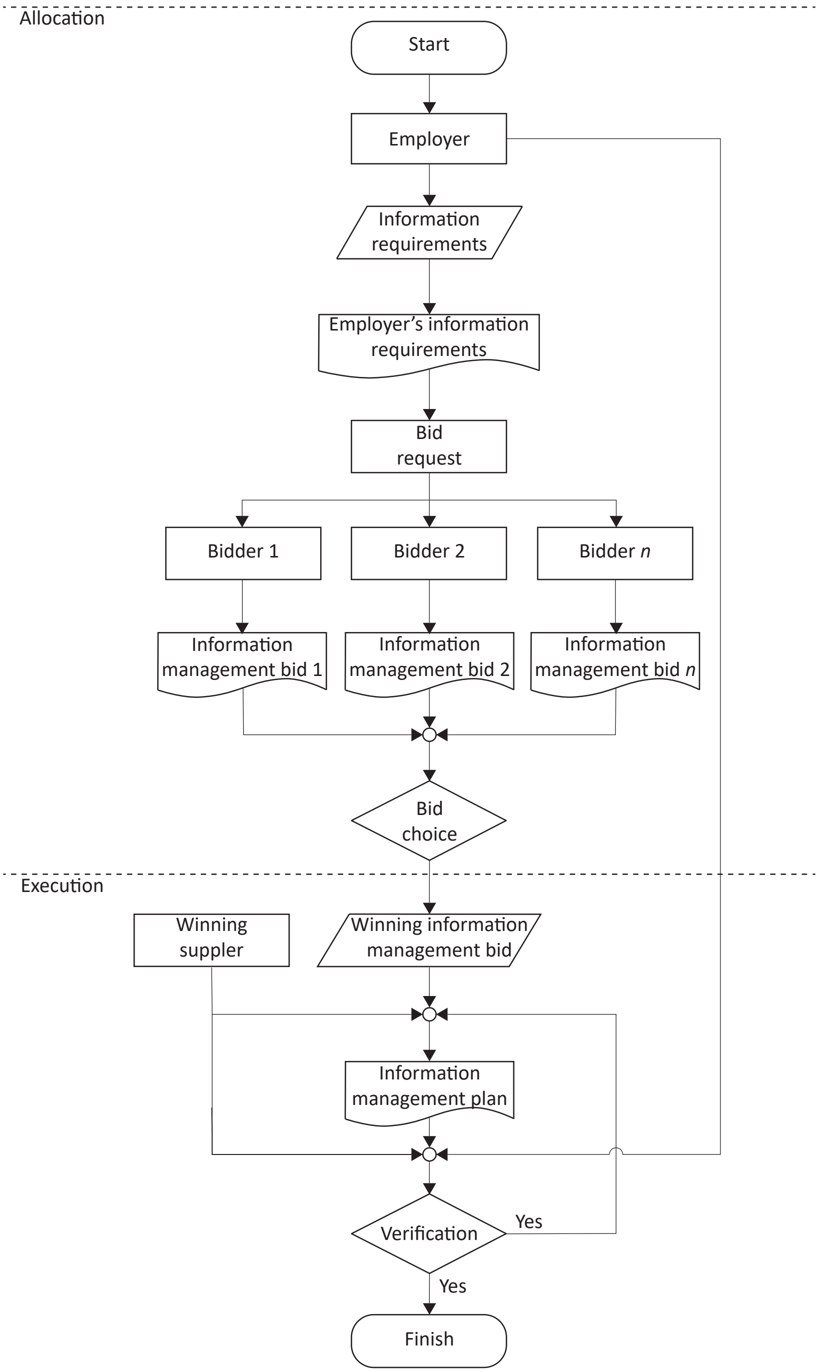


Figure 62 Informative Flow (UNI 11337-5:2017).

The standard then deals with defining and explaining the documents necessary for the information management, always looking at the British standards. So, the informative flow is organized as in Figure 62 and is composed of the three elements: Informative Specifications, offer for Information Management and Information Management Plan.

As shown in the diagram, the Informative Specifications, drawn up by the client before the award procedure, contain all the informative requirements. These requirements must concern both the technical area (e.g. contractor skill, the type of infrastructure, the characteristics of the hardware or the size of the models, etc.) and the management one (e.g. definition of roles, objectives, and uses of the model, verification and assessment procedures, phase management methods, etc.). Then, each interested contractor, therefore, prepares the offer for Information Management, in which the needs expressed by the client are met. Therefore, once the client chooses who will be the contractor, the winner company will have to prepare the Information Management Plan, with more specific and deepened information about the offer previously prepared.

The standard also deals with the management of information content. The purpose is to ensure the completeness, transmissibility, and consistency of the information contained. For that, the Information Specifications and/or the Information Management Plan documents must at least contain an explanation of:

- which single models must be prepared (number and type);
- what are the single models to be aggregated;
- rules for the management of interference (Clash Detection);
- rules for regulatory audits (Rule Set);
- the rules for managing information inconsistencies (Code Checking);
- the roles and responsibilities of the persons called upon to manage and resolve the criticalities highlighted in the previous steps.

In these minimum requirements, it is interesting to note that there are specifications for the single models and the federated one. Depending on the complexity of the project, these models can be subdivided into as many functional and necessary different parts are required. Then, all these single models must then be aggregated into the federated model. For that reason, a precise definition of common procedures for all the stakeholders involved is strictly required: the document deepens the part of model-checking by explaining three levels of coordination for each of which shows example diagrams.

UNI 11337-6:2017 The 11337-6:2017[92] is closely linked to that previous part. As the title suggests, the objective of this document is to provide specific procedural indications and a general draft example of the Informative Specification.

So, after the first introductory part and the presentation of a hypothetical index, the standard explains in detail an example of Informative Specification. This case study proposed is not exhaustive since we are talking about a contractual document that is drafted by a specific client according to their own economic needs, abilities, and requests on the specific project.

As could be expected from what was said in the previous part, the proposed structure of an informative specification and organized in four parts:

- Introduction;
- Standards;
- Technical Section;
- Management Section.

UNI 11337-7:2018 The last published part is the 11337-7:2018[93]. This standard describes requirements for the building information modeling professional profiles. These requirements are identified in terms of knowledge, skills, and competence, under the European Qualifications Framework, EQF. The requirements are indicated for the assessment of informal and non-formal learning outcomes and the conformity assessment of competences.

Unlike what has already been said in part 5, this document, published at the end of 2018, identifies one more figure, so four distinct professions. They are key figures for the management of a BIM process, thus introducing diversification with the most widespread international customs.

These BIM key figures are:

- CDE manager - Manager of the Common Data Environment;
- BIM manager - Digitized Process Manager;
- BIM coordinator - Coordinator of order information flows;
- BIM specialist - Advanced operator of information management and modeling.

92 UNI/TR 11337-6:2017 - Building and civil engineering works - Digital management of the informative processes - Part 6: Guidance to redaction the informative specific information.
93 UNI 11337-7:2018 - Building and civil engineering works - Digital management of the informative processes - Part 7: Knowledge, skill and competence requirements of building information modelling profiles.

Subsequently, for each figure, the requirements of knowledge, ability, and competence are indicated within an appropriate table in the standard. They must have these skills in order to fulfil the identified tasks. In particular, knowledge achieves through learning; ability to apply knowledge to complete tasks and solve problems; competence to use, responsibly and independently, knowledge and personal skills in a work situation.

Find appropriately qualified employees or train or update internal staff, are shared and common needs by all the protagonists of the construction supply chain who want to adopt the BIM. So, a standard that specifies whether the training activity of the subjects involved was long overdue.

With the publication of this part, too, the standard framework, necessary to allow the complete practicability of the BIM methodology in the Italian context, is being progressively and rapidly shaped. We now await the next parts, coordinated with the ISO published last year, to get the full picture.

4 OPTIMIZATION

Human activity proceeds with continuous decision-making. Result of cognitive and emotional processes, decisions determine the selection of a solution among different alternatives. In some cases, this process is automatic and straightforward, while in other cases, making a decision can be the result of a more extended, demanding and complicated process.

A design project in the construction industry is a complex activity that requires the designer to make countless choices to achieve different objectives, even different ones. Besides, he is called upon to consider multiple aspects, estimate potential risks and refer to intangible, subjective, and uncertain issues.

Architects have the task of making critical design decisions, and any mistakes made generally have a significant impact on the final result. For this reason, optimization methods are used in architectural design to support engineers in making the right design decisions. Digital evolution has allowed all designers to use increasingly sophisticated computers and software and to rely on them for more complicated designs and simulations. Also, thanks to the exponential increase in computing power, it has made it possible to incorporate optimization techniques into the design to support engineers in making decisions when there are many factors to consider and the optimal solution is not easily found.

This chapter will deal with the topic of optimization. In section **4.1**, it will be presented from a more general point of view to frame the issue and provide some historical hints of its development and applications. Optimization in the construction sector will be addressed in section **4.2**. Finally, in paragraph **4.3**, the optimization techniques will be presented, selecting from the vast reference literature those most used in the design field.

4.1 The Theory of Decisions

"There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things."

Niccolò Machiavelli

Deciding, from the Latin decīdĕre result of de - caedĕre "cut" then properly "cutaway", indicates the action of choosing between different things or possibilities[1]. The decision-making process is the result of cognitive and emotional processes, which determine the selection of a line of action among different alternatives. In daily life, decisions are continually made. In some cases, decisions are automatic, while in other cases, making a decision can be a more extended, more demanding, and complex process. To make articulate and difficult choices when faced with several comparable or non-comparable options or when it is necessary to make a classification it is convenient to use strategic planning to solve this system, i.e. apply a series of generally sequential procedures with many feedbacks to find the most favourable result[2]. The solution must be identified by one or more decision-makers among multiple options based on the information available, assuming values on intangible and subjective issues, identifying and estimating potential risks, and most often confronting uncertainties that only the future can reveal.

The best or most appropriate or optimal theoretical solution, which is obtained as a mathematical solution that emerges from a model, can serve as a benchmark for deciding the final choice. Often there is not too much interest in adopting the "optimal" solution from a mathematical point of view. However, but one prefers the one that best satisfies the objectives of the decision-maker(s), also considered a non-rational and subjective component of the person linked to the responsibility behind some choices.

Operational research (OR), also known as decision theory or management science, provides mathematical tools to support decision-making where limited activities and resources need to be managed and coordinated in order to maximise or minimise an objective function. Operational research is concerned with formalizing a

1 Traslation of the Italian definition from the Encyclopedia Treccani, *Dizionario della lingua italiana* (www.treccani.it

2 Munier, N., 2011. A Strategy for Using Multicriteria Analysis in Decision-Making: A Guide for Simple and Complex Environmental Projects, 2011 edition. ed. Springer, New York.

problem into a mathematical model and calculating a solution that is optimal, when possible, or close to optimal for it. It is a scientific approach to solving complex problems; it can be traced back to the field of applied mathematics but has strong interdisciplinary characteristics. It has many applications in the economic, infrastructural, logistic, military, service, and transport system design and technology fields. For example, in the particular case of economic problems, the function to be maximized may coincide with the maximum profit obtainable or the lowest cost to be incurred. It can be used in linear programming (problem planning); dynamic programming (sales planning); network programming (project management); queue theory (to manage traffic problems); stock theory (warehouse storage); graph theory (used for communication networks); game theory (decision problems under competitive conditions).

Decision theory plays an important role in decision-making because it allows the best choices to be made to achieve a given objective while respecting constraints that are imposed from outside and are not under the control of those who have to make the decisions. Operational research does not replace decision-makers but, by providing solutions to problems obtained by scientific methods, allows rational choices to be made.

The origins of Operational Research can be found in the 16th century when the precursors of this discipline began to employ a scientific approach to the management of organizations[3]. However, the real birth of this sector is fixed before the Second World War and the military field: the OR was used to decide which of all military operations and specific activities to assign the remaining available resources.

Between 1935 and 1937, the United Kingdom worked on the radar project as an anti-aircraft defence, but it was vital to locate and subsequently intercept and return British aircraft to the ground. It was therefore essential, first of all, to optimise the distribution of radar equipment on the territory and, secondly, that the signal was sent by radio to appropriate locations. Thus, the “Biggin Hill Experiment” was born, which was the first attempt to integrate the data obtained from radar with those observed on the ground.

The British General Staff, first of all, and then also the United States, required the commitment of scientists who, through a scientific approach, would find the solution to this problem in the field of military operations, hence the name of research

3 Gass, S.I., Assad, A.A., 2004. An Annotated Timeline of Operations Research: An Informal History, 2005 edition. ed. Springer, New York.

in (military) operations[4]. In 1939, the physicist Patrick Maynard Stuart Blackett[5] was called to constitute a research group composed of scientists and military personnel, engaged in the fight against German submarines. The success obtained by this group passed to history, produced the result of multiplying, in the United Kingdom and the other allied Countries, research groups with similar characteristics.

The first organized OR activity in the United States began in 1942 in the Naval Ordnance Laboratory. This group, which dealt with the problems of war with mines, was later transferred to the Navy Department, from which it designed the blockade of aircraft mines in the Inland Sea of Japan. Moreover, as in Britain, radar stimulated developments in the US Air Force. In October 1942, all Air Force commands were invited to include operational research groups in their personnel. By the end of World War II, there were 26 such groups in the Air Force. In 1943, General George Marshall suggested that all commanders should form teams to study amphibious and ground operations.

The activity of these groups was called Operational Research in Great Britain and later Operations Research in the United States. A.P. Rowe, superintendent of the "Bawdsey Research Station", in 1938, used the expression "operational research" to describe the type of activity developed in a final technical report of the project.

During the Second World War, more than 700 scientists were employed in the UK, Canada, and the USA. The studies conducted on the optimal management of anti-submarine operations and the transfer of convoys were the "winning secret weapon" in the North Atlantic battle, as defined by the physicist Ellis Johnson, director of the US Military Office of Operational Research (Figure 63).

In 1945 the British Marxist crystallographer and intellectual J. D. Bernal went so far as to suppose that in the war OR represented not a new profession, but a total realignment in the relations between science, state, and society. He calculated that the moment marked the beginning of a entirely new era in history in which human progress could be intelligently planned[6].

The end of the conflict determined a change of the approach until then used only for war purposes, orienting it towards civil problems (such as the location of industrial warehouses, the mixing of loads of a road haulage service) generated by the post-war industrial boom, with the relative increase in complexity and specializa-

4 Hillier, F.S., Lieberman, G.J., 2009. Introduction to Operations Research, 9 edition. ed. McGraw-Hill Science/Engineering/Math, New York.

5 Patrick Maynard Stuart Blackett was a British physicist and lecturer at Cambridge University, University of London, University of Manchester and Imperial College. He also won the Nobel Prize for Physics in 1948.

6 Bernal, J. D., 1975. Lessons of the War for Science [1945]. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 342, No. 1631, pp. 555-574.

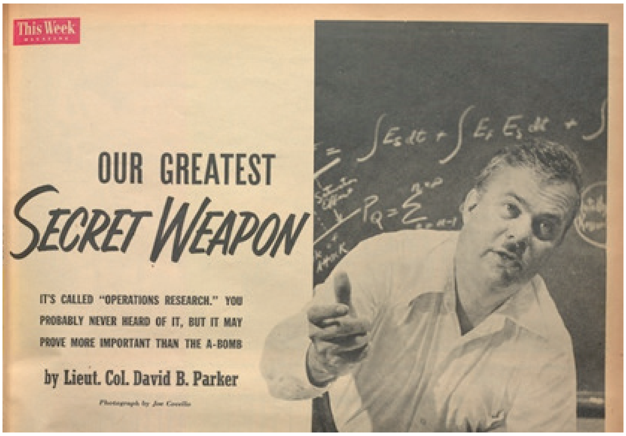


Figure 63 Historical image reported in "This Week Magazine" in the early post-war period by Ellis Johnson with his revelation of the "best secret weapon".

tion. The first civil applications were in the oil industry because initially, only large industries could afford such studies.

The first Operational Research Associations were also born and still exist today: in Great Britain, the "OR Society"[7] was born in 1948. in 1952 in the United States, the "ORSA - Operations Research Society of America", which today is called INFORMS - INstitute For Operations Research and Management Sciences[8] and in 1961 the Italian "AIRO - Associazione Italiana Ricerca Operativa" was born[9].

The OR became an academic discipline in 1948 when a course in non-military techniques was introduced at the Massachusetts Institute of Technology in Cambridge. In 1952 a curriculum was established leading to a master and doctorate at the Case Institute of Technology (now Case Western Reserve University) in Cleveland. Since then, many prestigious academic institutions in the United States have introduced programs. In the UK courses were started at the University of Birmingham in the early 1950s. The first president of operational research was created at the newly established University of Lancaster in 1964. Similar developments have taken place in most countries where a national operational research company exists. The first academic journal, the Operational Research Quarterly, published in the United Kingdom, was launched in 1950; in 1978, its name was changed to the Journal of the Operational Research Society. It was followed in 1952 by the Journal of the Operations Research Society of America, which was renamed Operations Research in 1955. The International Federation of Operational Research Societies began the International Abstracts in Operations Research in 1961.

7 More information available on www.theorsociety.com
8 Further information available on www.informs.org
9 More information available on www.airo.org

There is not a single codified and globally accepted definition of Operational Research because each association has written its definition. Therefore only the one given by the English association is reported because it highlights the fundamental aspect of this discipline, which is to help the decision-maker in dealing with complex problems of the real world, even if this research can become abstract and detached from reality.

"OR is the application of the methods of science to complex problems arising in the direction and management of large systems of men, machines, material, and money in industry, business, government, and defence. The distinctive approach is to develop a scientific model of the system, incorporating measurements of factors such as chance and risk, with which to predict and compare the outcomes of alternative decisions, strategies, or controls. The purpose is to help management determine its policy and actions scientifically"[10].

Decision theory has had a rapid spread and growth due to two main factors: the first is the encouragement that was given to scientists who participated in research groups during the war, and that determined the progress of operational research techniques; the second is the computer revolution, which could provide the resources to perform calculations of this magnitude. This second factor was decisive because it allowed from 1980 onwards, with the increase in the potential of personal computers, to make operational research accessible to an increasing number of people and to move from small to medium and large problems that typically constitute reality.

Nowadays, the operational search can have multiple software, including some free of charge, and is used and appreciated in many fields[11]. Some examples are given in the various sectors to present the vastness of applications, but a more exhaustive list of real cases can be found on the INFORMS website[12].

Finance

- Choice of investments from a wide range of possibilities while respecting the constraints of a financial budget and maximizing earnings;
- Portfolio composition: deciding which securities and shares to invest capital in order to maximize earnings or minimize risk.

Industry

- Production planning: determining production and/or resource utilisation levels, e.g. optimal allocation of resources, distribution of limited resources between competing alternatives in order to minimise cost or maximise profit.

10 Duckworth, W.E., Gear, A.E., Lockett, A.G., 1977. A Guide to Operational Research. Springer Netherlands, Dordrecht. Tadei, R., Croce, F.D., 2010. Elementi di Ricerca Operativa. Società Editrice Esculapio.
11 Serafini, P., 2009. Ricerca Operativa, UNITEXT. Springer Milan, Milano.
12 www.informs.org

- Excellent stock management: decide when and how much, during a production process, products should be stored in order to meet deliveries while minimizing costs.
- Plant location and sizing: deciding where to install production plants in order to optimally supply areas spread over a territory, e.g. where to build the base stations of a telecommunications network and the transmission power to cover the territory.

Optimization design

- Network design and management: define the connections and size the capacity of a road, telecommunication, data transmission, and circuit network in order to guarantee traffic between the various origins and destinations and minimize the overall cost;
- Structural design: define the design of a building so that it can best withstand stress from external agents (earthquakes, strong winds) or the design of the profile of an aircraft wing so that, for example, the lift is maximised;
- Optimal allocation of electronic components: designing a motherboard so that, for example, the lengths of the electrical signal paths are minimized.

Organization

- Determination of staff shifts: covering a range of services under company contract constraints and minimizing costs
- Maintenance of goods: decide when and if to carry out maintenance of certain items subject to wear and tear, to minimize the overall cost.
- Routing of vehicles: deciding which routes a fleet of vehicles (e.g. refuse collection vehicles or distribution of products to a network of shops) should follow in order to minimise the overall distance traveled;
- Project planning: deciding how to manage resources and how to sequence the multiple activities of a project.

The theory of the decision was not primarily born for the construction sector, but given its potential, it was also introduced in this area. The primary purposes are: to determine the optimal form according to one or more parameters such as free solar energy; to design the optimal structure according to the wind or the stresses caused by an earthquake; to manage the construction site or the entire project by optimizing the sequence of the various activities to minimize time; etc. Other applications could be listed, but what is interesting is that this discipline can also be extended to other aspects and can, therefore, be used to support the designer to make choices oriented towards sustainability.

4.2 Optimization in the Construction Industry

The concept of design was born the first time an individual created an object to satisfy human needs. Today design is still the highest expression of the art and science of engineering. From the earliest days of engineering, the goal has been to improve the design in order to find the best way to meet human needs with the means available[13].

The design process can be described in many ways, but there are some aspects in the process that each description must contain: an acknowledgment of need, an act of creativity, and the selection of alternatives. Correctly, the following stages of the process can be identified:

- recognition of the need or objective;
- identification of the problem;
- creation of one or more physical configurations;
- study of the performance of the individual configurations;
- selection of the best alternative;
- testing of the prototype made.

The selection of the best alternative is the optimization phase of the project. In the field of construction, this is undoubtedly an important choice, which in addition to being complex, it also brings multiple responsibilities, since other people will use the building or will be conditioned by the designed space. Many projects also have a long life, surviving that of the people who worked on the design and construction. There are large-scale projects, such as the construction of new infrastructure (high-speed railways, tunnels, or bridges) or even the design of new neighbourhoods or cities, and there are small-scale projects. Although they have different societal influences and resource demands, the underlying design principles are common in all projects.

Designers have the task of making important design decisions and any mistakes made generally have a significant impact on the final result. For this reason, much effort is spent on the initial design of the architecture. However, the alternatives evaluated, compromises, and rationalisations on the decisions made remain in the designer's head. The entire process and logic behind architecture are usually not documented because the focus is only on the results of the decisions, i.e. the architectural artefacts.

13 Papalambros, P.Y., Wilde, D.J., 2000. Principles of optimal design: modeling and computation, 2nd ed. Cambridge University Press, Cambridge; New York.

The use of computers and some of the techniques used to help decision-makers is now widespread in the construction sector as well. There are computer programs written to help the decision-making process, although not to solve the problem, at least to shed light on the question of the decision, where many factors must be taken into account as in a building project.

One of the most common areas of application of optimization is structural design, in order to maximize the performance and efficiency of the material application while minimizing life cycle costs. The techniques that attempt to improve or find the best mechanical structures can be classified into three categories:

- **Optimization of sizing**
  Without changing the general shape, an optimal relationship between weight, rigidity, and dynamic behaviour is achieved by optimising sheet thicknesses. In the early design stages a free sizing approach helps to obtain the best indications for sheet partitioning, and in the subsequent design stages sizing optimization can lead to optimal thicknesses for all individual sheets in the structure.
- **Shape optimization**
  This optimization method determines the optimal shape of the structure with the specified sheet thicknesses by slightly modifying the surface geometry to minimize stress peaks, which in turn positively affect fatigue life.
- **Topology Optimization**
  It is a mathematical method that optimizes the material layout within a given design space for a given set of loads, boundary conditions, and constraints with the aim of maximizing system performance. Unlike size and shape optimization, structures optimized through topology optimizations can achieve any shape within the design space.

Optimization techniques have also been used for other aspects of the project, such as spatial allocation problems, as well as for shape optimization or design of plant systems and many others[14]. In parallel with the spread of optimisation practices, computers and programs used in construction have increasingly evolved.

Digitization continues to change the world of engineering and design, increasing the complexity of what can be designed and built. In today's increasingly competitive global marketplace, by exploring and exploiting new ways of using information technology tools, we can expand the perceived boundaries of possibilities and

14 Bandara, P., Attalage, R., 2013. Optimization Methodologies for Building Performance Modelling and Optimization. National Engineering Conference 2012, 18th Eru Symposium, Faculty Of Engineering, University Of Moratuwa, Sri Lanka.

create increasingly innovative projects with increasingly complex geometries. Architecture is now designed and built using the tools of the digital world: from parametric and CAD modeling to automated production, up to the analysis and use of Big Data. A computer connected to manufacturing machines is now an essential part of the design process.

Today almost every architect uses a computer and can also rely on programming languages and the potential of software for generating complex structures, construction codes, and design. Today we talk about computational design, a broad term that includes many activities based on which rely on programming languages: from the management of Big Data to the automated generation of forms.

Today we can, therefore, speak of computational design used for design optimization. Computational models enable iterative computing, both interactive and automated, to be used to find feasible, performance-oriented design alternatives that would be difficult to achieve using only conventional computational and design processes. These processes build on and incorporate other emerging design computing technologies, including algorithmic design, parametric and associative 3-D geometry, performance-based design, integrated design tools, and design automation.

Many design parameters can be varied, and their impact on different design performance is increasingly predictable. Nowadays, using the considerable computing power of computers, computational optimization processes can set up to quickly generate, evaluate, and mediate between thousands of design variants. Through the computation of design rules, parameters (parametric modeling) can be assigned to a standard design, whose immediate effects can be displayed in the software interface. By modifying these parameters, different solutions can easily obtain, which meet specific criteria. The result of the process is a set or cloud of optimized design results, from which the final solution can be selected according to preferences between the performance achieved and the objectives set.

The set optimization process also has the advantage that it can be adjusted, adapted, and repeated to study the impacts of other parameters or processes. Computational optimization can, therefore, with a small initial effort, provide designers with a replicable and useful tool to determine the best compromise between different design objectives, desired performance, and costs, as well as facilitate multidisciplinary negotiations. It is clear that the use of a process of this type from the earliest stages of conception makes it possible to improve the quality of the design, to reduce time, therefore also costs, and making it possible to reach new levels of complexity.

Computational design, an excellent means of managing the complexity caused by the interaction of factors over which we have control or the uncertainty surrounding factors that do not interest us, has traditionally been applied primarily to niche projects. However, all projects are complex in their way and can benefit from this approach, so over time; several IT tools have developed that are now available to everyone on the market. Most of these tools rely on and are directly linked to other digital modeling software platforms, such as Rhinoceros[15] or Revit[16]. Grasshopper[17] is undoubtedly the most popular computational design tool. Applications such as Grasshopper, thanks to the visual programming language, allow programming through graphic manipulation of elements and not through written code. They also allow inserting elements of programming code in order to integrate additional elements such as mathematical formulas. Therefore, these tools, it is possible to write optimization processes, based on methods derived from operational research to be used in the identification of optimal design solutions.

15 Rhinoceros, commonly called Rhino, is a commercial 3D surface modeling application software developed by Robert McNeel & Associates, a company based in Seattle, Washington, USA. More information available on www.rhino3d.com

16 Autodesk Revit is a CAD and BIM program for Windows operating systems, created by Revit Technologies Inc. and purchased in 2002 by Autodesk, which enables design with parametric modeling and drawing elements. More information available on www.autodesk.eu/products/revit/overview

17 Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application. David Rutten created the program at Robert McNeel & Associates. Programs are created by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components. Further information available on www.grasshopper3d.com

4.3 Methods of Decision Support

The reference literature on the analysis of the way people make decisions (prescriptive theories) or the way people should make decisions (normative theories) is extensive and growing. At the same time, however, the development of the perfect method for rationalising decision-making remains an elusive objective.

The decision-making process is intuitive when considering problems related to individual criteria since the decision-maker is only called upon to choose the alternative with the highest rating. However, when, on the other hand, the decision-maker has to evaluate alternatives with multiple criteria, many problems, such as the weighting of criteria, dependence on preferences, and conflicts between criteria, the decision-making process is more complicated and can be tackled with more sophisticated methods.

There are many rigorous scientific approaches, but according to many authors, the best known and used for problems similar to those found in a decision-making process in architectural design is Multi-Criteria Decision Making (MCDM)[18].

In order to address problems related to decision making based on multiple criteria (MCDM), the steps to be taken are[19]:

- identify the problem: understand how many attributes or criteria exist in the problem;
- build preferences: collect appropriate data or information about the decision maker's preferences and how they can be taken into account when solving the problem;
- evaluate alternatives: identify a range of possible alternatives or strategies to ensure that the objective will be achieved;
- find and determine the best alternative: select an appropriate method that will help to assess and exceed our level of expertise and enable us to find possible alternatives or strategies.

In the broad field of MCDM, problems can be classified into two main categories[20]: multi-attribute decision-making (MADM) and multi-objective decision-making

18 Tzeng, G.-H., Huang, J.-J., 2011. Multiple Attribute Decision Making: Methods and Applications, 1 edition. ed. CRC Press, New York.
19 Simon, H.A., 1977. The new science of management decision, Rev. ed. ed. Englewood Cliffs, N.J.: Prentice-Hall.Papalambros et al. 2000. Ibid.Tzeng et al. 2011. Ibid.
20 Hwang, C.-L., Yoon, K., 1981. Multiple Attribute Decision Making, Lecture Notes in Economics and Mathematical Systems. Springer Berlin Heidelberg, Berlin, Heidelberg
21 Tzeng et al. 2011. *Ibid.*

(MODM), according to different purposes and different types of data. An informative overview of MCDM, summarising all the characteristics of the process and the main mathematical methods of each of the two subcategories - MADM and MODM - was presented by Tzeng and Huang in 2011 (Figure 64)[21].

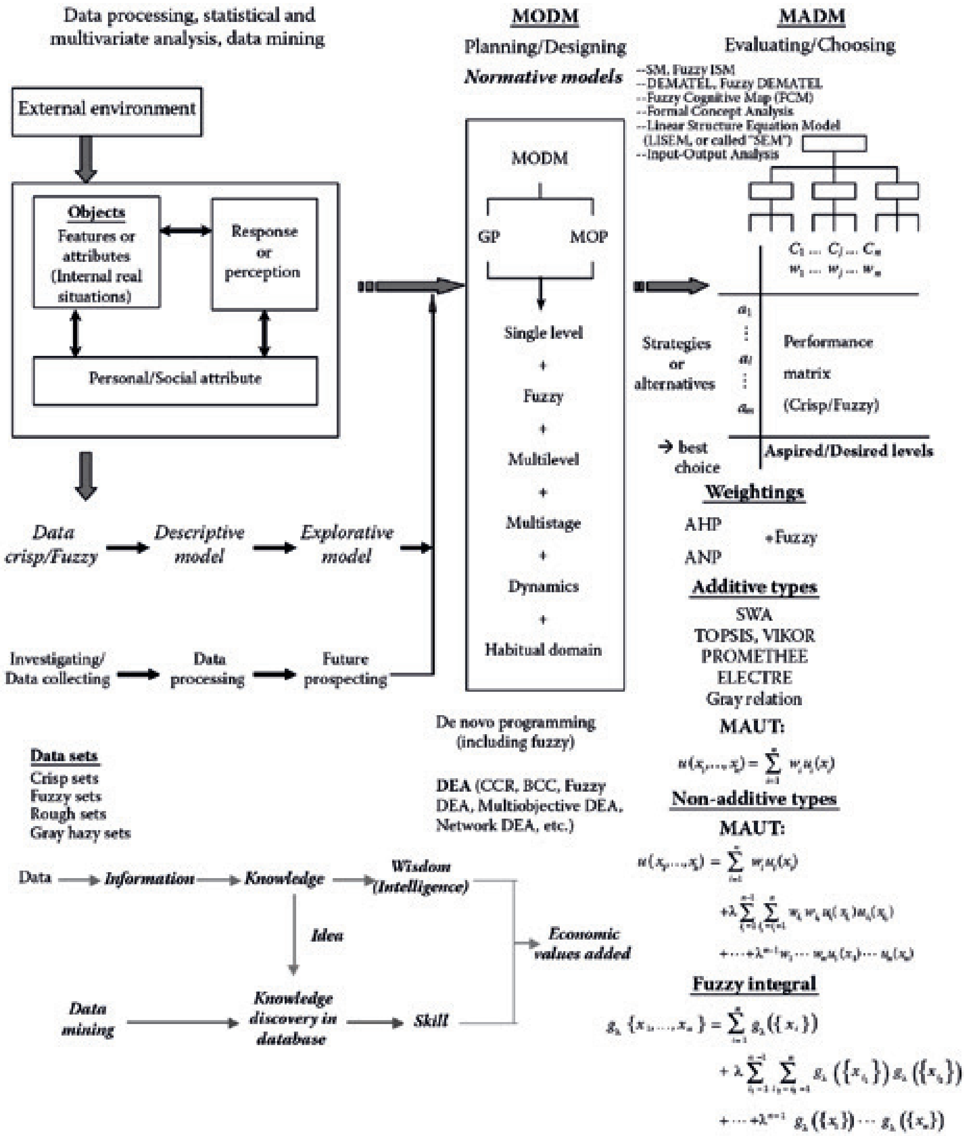


Figure 64 Profile of MCDM (Tzeng and Huang 2011).

Multi-attribute decision methods (MADM) are usually used to identify the optimal decision between a finite number of predetermined alternatives and discrete preference classifications. Such a problem can be represented in a matrix form using a matrix [m,n] whose generic x_{ij} element represents the value of the j-th attribute for the i-th alternative; the A_n columns represent the attributes, and the d_m rows represent the alternatives (Figure 65).

Alternatives or decisions	Attributes				
	A_1	**A_2**	**A_3**	**…**	**A_n**
d_1	x_{11}	x_{12}	x_{13}	…	x_{1n}
d_2	x_{21}	x_{22}	x_{23}	…	x_{2n}
…	…	…	…	…	…
d_m	x_{m1}	x_{m2}	x_{m3}	…	x_{mn}

Figure 65 Matrix representing a multi-attribute decision-making problem.

The MODM are especially suitable for the design/planning facet, which aims to achieve the optimum, considering the various interactions within the data constraints. In this way, you get infinite alternatives that allow you to pursue the goal as much as possible, but without knowing what is and if there is, in reality, the ideal optimum solution. As represented in Figure 66, the dots represent the solutions of the problem, two criteria define the plane on which the alternatives are found.

Before proceeding in the next paragraphs in the details of the two categories, it is necessary to dwell on some terminologies typically used in this discipline and define their precise meaning.

The “alternatives”, already widely referred to as solutions, are the decisions available to the decision-maker.

The “attribute” indicates a characteristic or quality of the alternatives, e.g. in the case of an insulating material, it could be price, conductivity, density, etc.

When the direction of an attribute is specified, it makes an alternative more attractive and it becomes a “criterion”. In turn, the criterion is divided into goal and target. The first indicates the goal to be pursued as far as possible, and the second is the condition to be achieved.

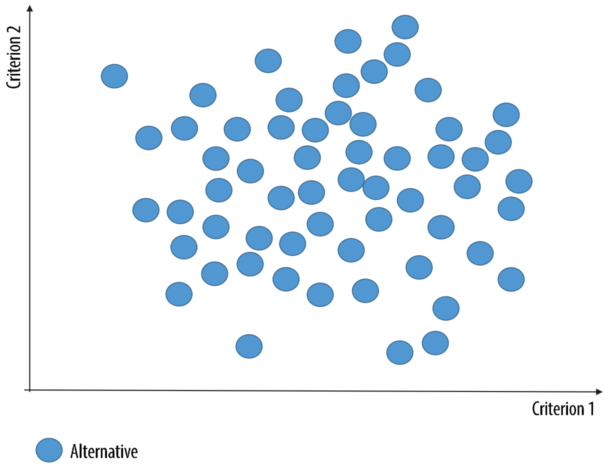


Figure 66 Representationon C_1, C_2 plan of the possible alternatives.

Finally, "constraints" are the conditions that must be respected by possible decisions.

The subtle and challenging distinction between attribute and criterion is precisely the same that is found in distinguishing multi-target problems from multi-attribute problems.

All the decision-making methods that will be presented in the following pages can be represented by a common structure (Figure 67), and all of them intervene in the phases of analysis and evaluation of alternatives to determine an optimal solution of the problem or a good approximation of it.

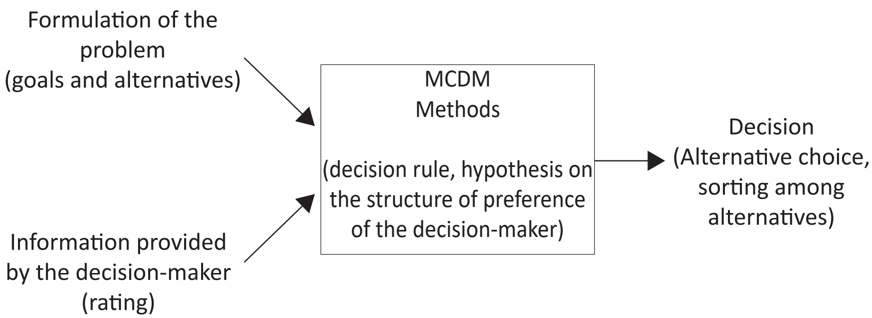


Figure 67 Basic structure of MCDM methods.

4.3.1 Multi-Attribute Decision Methods

The historical origins of the MADM can be placed with the discussion of the St. Petersburg paradox between Nicolas Bernoulli (1687-1759) and Pierre Rémond de Montmort (1678-1719). The St. Petersburg game identifies the following problem: "A game is played by flipping a fair coin until it comes up tails, and the total number of flips, n, determines the prize, which equals \$2 × n. If the coin comes up heads the first time, it is flipped again, and so on. The problem arises: how much are you willing to pay for this game?"[22]

According to the expected value theory, it can be calculated that $EV = \sum_{n=1}^{\infty}(\frac{1}{2})^n \cdot 2^n$ the expected value will go to infinity. However, this result goes against human behaviour, as no one is willing to pay more than \$1000 for this game. The first answer to the St. Petersburg paradox was given by Daniel Bernoulli (1700-1782) with the publication of his research on utility theory in 1738. Leaving aside the specific aspects that describe the solution of the St. Petersburg paradox in detail, the conclusion he comes to is that human beings make decisions based not on expected value, but utility value. This behaviour also occurs when dealing with the problems of MADM.

About two centuries later, von Neumann and Morgenstern published their book "Theory of Games and Economic Behavior"[23] in 1947. They describe a mathematical theory of economics and social organization based on game theory. This work opened the doors to the development of MADM (Figure 68).

A first organization of the methods can be made by dividing them into two macro-categories[24]: those based on the multiple attribute utility theory (MAUT) and the higher-ranking methods, such as the ELECTRE[25] or PROMETHEE[26] methods that will be described later.

Based on Bernoulli's utility theory, the Multiple Attribute Utility Theory (MAUT)[27] was developed. This theory allows to determining the preferences of the decision-maker, which can usually be represented as a hierarchical structure, using an appropriate utility function. By evaluating the utility function, the best alternative

22 Bernstein, P.L., 1998. Against the Gods: The Remarkable Story of Risk. John Wiley & Sons.
23 von Neumann, J., Morgenstern, O., 1947. Theory of Games and Economic Behavior. 2ed. Princeton. Princeton University Press.
24 Tzeng et al. 2011. *Ibid.*
25 Benayoun, R., Roy, B., Sussman, N., 1966. Manual de Reference du Program ELECTRE. Note de Synthese et Formation, Direction Scientifique SEMA, No. 25, Paris, France.
26 Brans, J.P., Mareschal, B., Vincke, P., 1984a. PROMETHEE: A new family of outranking methods in MCDM, Operational Research, IFORS'84, North Holland, 477–90.
27 Fishburn, P.C., 1990. Utility Theory and Decision Theory, in: Eatwell, J., Milgate, M., Newman, P. (Eds.), Utility and Probability, The New Palgrave. Palgrave Macmillan UK, London, pp. 303–312. https://doi.org/10.1007/978-1-349-20568-4_40

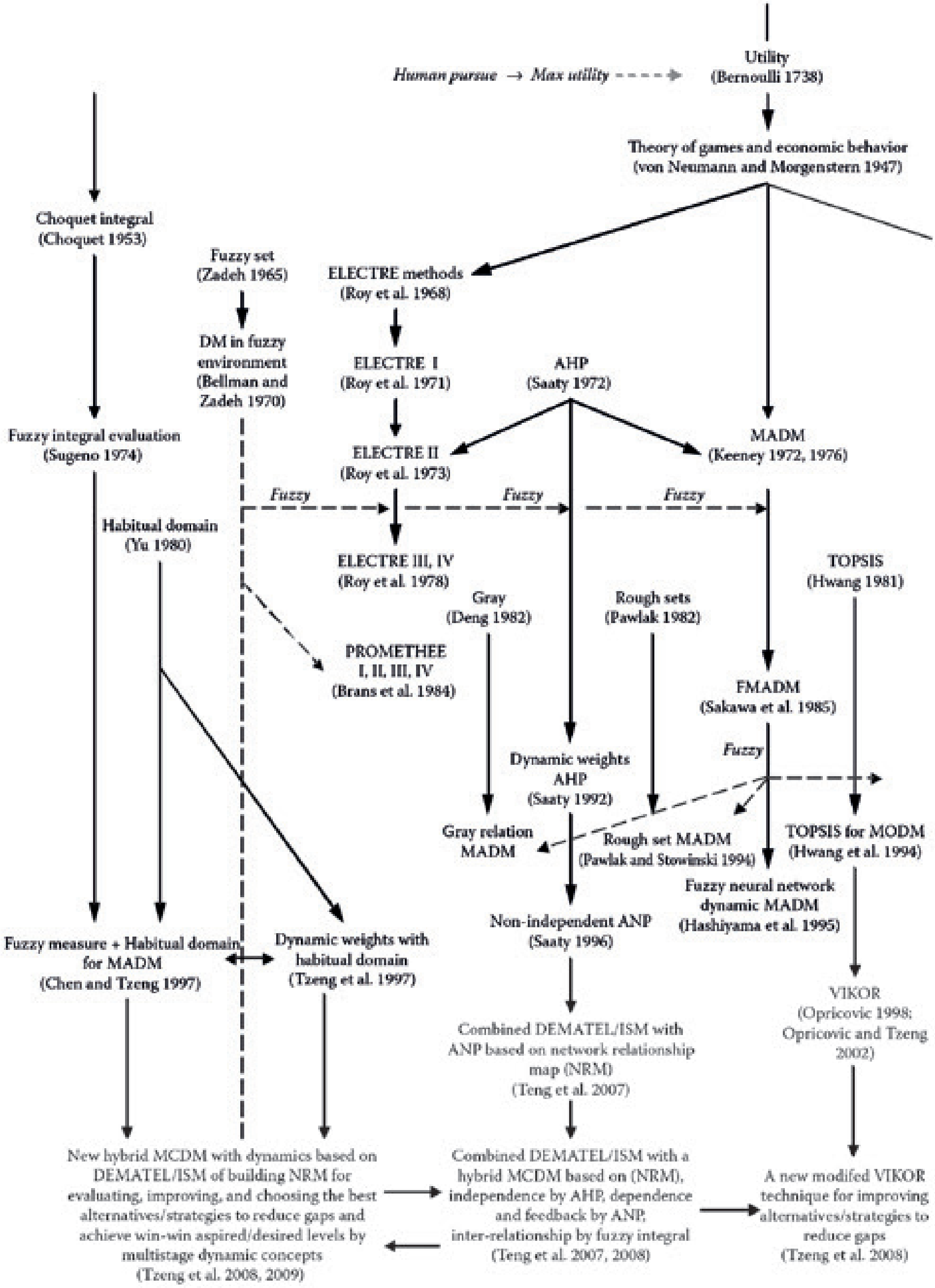


Figure 68 Outline of the development of MADM methods (Tzeng and Huang 2011).

with the highest utility value can be easily determined. Although many documents have been proposed to determine the appropriate utility of the MAUT function, the main criticism of MAUTs is related to the unrealistic assumption of preferential independence[28]. That is the result of preferring one criterion over another is not affected by the remaining criteria. To overcome this problem, the integral Choquet[29] was proposed. The integral Choquet can represent a specific type of interaction between the criteria using the concept of redundancy and support/synergy.

In 1965, fuzzy sets[30] were proposed to address the problems of linguistic or uncertain information and be a generalization of conventional set theory. With successful applications, fuzzy sets have recently been incorporated into MADM to address MADM problems in situations of subjective uncertainty.

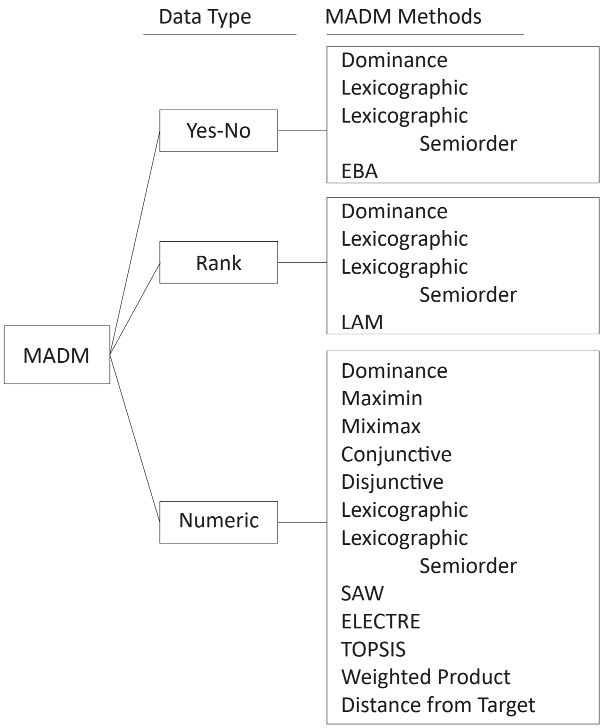


Figure 69 Classification of MADM methods based on data type (Chen and Hwang 1992).

28 Bouyssou, D., Marchant, T., Pirlot, M., Perny, P., Tsoukias, A., Vincke, P., 2000. Evaluation and Decision Models: A Critical Perspective, International Series in Operations Research & Management Science. Springer US. https://doi.org/10.1007/978-1-4615-1593-7

29 Choquet, G., 1954. Theory of capacities. Annales de l'institut Fourier 5, 131–295. https://doi.org/10.5802/aif.53

30 Zadeh, L.A., 1965. Fuzzy sets. Information and Control 8, 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X

Throughout this long journey, numerous MADM methods have been developed and are now present in the reference literature. Each method has its specific characteristics, and there are several ways to classify them.

A possible classification can be made based on the type of data used (Figure 69)[31], but since there are cases where data belonging to different categories are used, this classification is not widely used. It is also possible to classify methods based on the number of decision-makers involved in the decision-making process[32], which can be a group or an individual. Alternatively, they can be arranged by the type of solution expected, i.e. whether the methods are used to screen alternatives or whether to evaluate/select them (Figure 70).

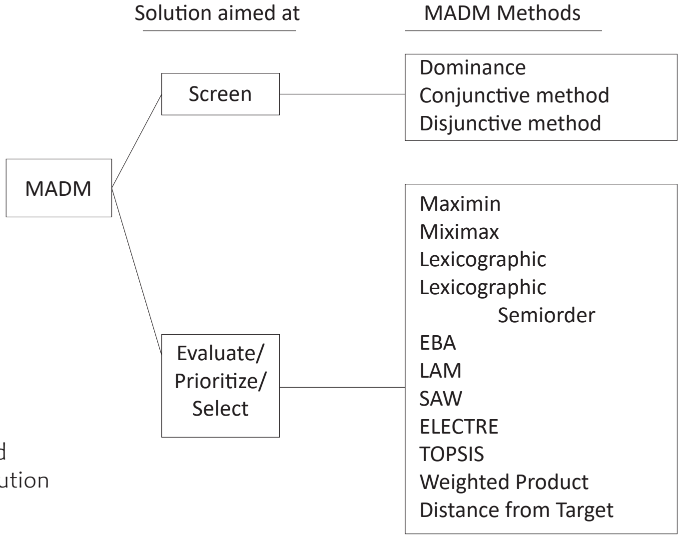


Figure 70 Classification of MADM methods based on the type of desired solution (Chen and Hwang 1992).

Finally, MADM methods can also be classified according to the type of information preferably provided by the decision-maker (Figure 71)[33]. Specifically, the following two options can be verified, and for each one, there are different resolution methods: no information or information on attributes. In the first case, the most used MADM methods without information from the decision-maker are Dominance,

31 Chen, S.-J., Hwang, C.-L., 1992. Fuzzy Multiple Attribute Decision Making, Lecture Notes in Economics and Mathematical Systems. Springer Berlin Heidelberg, Berlin, Heidelberg.
32 Chen et al. 1992. *Ibid.*
33 Chen et al. 1992. *Ibid.*

Maximin, Maximax. In the second case, different types of information from the decision-maker can be collected. For example:

- **Information on standard levels**
  The decision-maker indicates a set of acceptability levels for attributes. The most commonly used MADM resolution methods are Disjunctive and Conjunctive;
- **Ordinal Information**
  The decision-maker indicates the relative importance of the attributes without giving quantitative information. The most commonly used MADM resolution methods are lexicographic and elimination by aspects;
- **Cardinal information**
  The decision-maker provides a measure of the importance of the attributes, i.e. the so-called "weight" of each, and in this case, it is quantitative information. The most commonly used MADM resolution methods are, for example, the Simple Additive Weighting (SAW) Method, the Elimination Et Choice Translating Reality (ELECTRE) method, or the TOPSIS - Technique for Order Preference by Similarity to Ideal Solution Method.

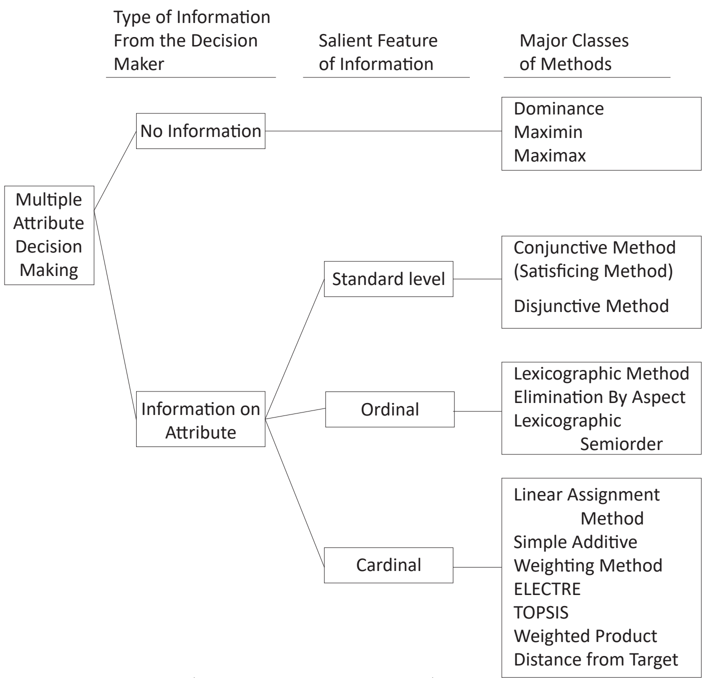


Figure 71 Taxonomy of MADM methods (Chen and Hwang 1992).

In the next pages, the ELECTRE, PROMETHEE, AHP, and TOPSIS methods will be presented as they are the most used methods[34].

ELECTRE Bernard Roy developed the method ELimination Et Choix Traduisant la Realité (ELECTRE). The first version dates back to 1968 but over time there have been several subsequent versions: ELECTRE I, II, III, IV, IS, and TRI.

All versions of this method have one fundamental characteristic in common: they aim to construct an order of alternatives that do not pretend to be complete, and so it is generally only a partial order, situations of alternatives that are not comparable with each other can be appended. The ELECTRE is a highly efficient multi-attribute decision-making method and uses weights assigned to the various attributes, but these have a limited value, as they cannot be used to compensate negative and positive values indiscriminately.

Like all higher-ranking methods, ELECTRE compares pairs of alternatives in each attribute to determine partial binary relationships that denote the strength of the preference of one alternative over the other. In ELECTRE, beyond certain levels - and here lies the philosophy of the method - the decision-maker does not accept this kind of trade-off. In front of two alternatives, d_i and d_k, the first one can be perfect for specific attributes, but not for others; instead the second one can be much better. It does not accept to identify which of the two prevails simply by weighing the values on all the attributes and prefers to consider the alternatives d_i and d_k not comparable.

ELECTRE uses the concepts of concordance and discordance and the parameters known as thresholds. The thresholds of preference (p), indifference (q) and veto (v) have been introduced in the ELECTRE method so that higher-ranking relationships are not wrongly expressed due to less important differences. The three thresholds are defined as:

- The preference threshold (p) is a value above which the decision-maker strongly prefers an alternative to others for the given attribute.
- The indifference threshold (q) is a value below which the decision-maker is indifferent between two alternatives for the given attribute.
- The veto threshold (v) blocks the higher-ranking relationship between the alternatives for the given attribute.

The ELECTRE method, in its simplest form, considers only the first two parameters, leaving aside the veto threshold.

34 Tzeng et al. 2011. *Ibid.*

The procedure can be illustrated first of all starting from a table in normal form:

	A_1	A_2	…	A_n
	w_1	w_2	…	w_n
d_1	x_{11}	x_{12}	…	x_{1n}
d_2	x_{21}	x_{22}	…	x_{2n}
…	…	…	…	…
d_m	x_{m1}	x_{m2}	…	x_{mn}

Consider two alternatives, d_i and d_k, wonder whether the first one can be considered better than the second. We divide the set of attributes into two subsets, J_{ik}^+ and J_{ik}^-, the one for which the first decision is better (or no worse) than the second, d_k, and its complementary where it is d_k that prevails over d_i.

As far as the J_{ik}^+ set is concerned, we want the sum of the weights of the attributes that compose it, which we will indicate with C_{ik}, called concordance index, to exceed the prefixed threshold (p). This can be expressed with the formula:

$$C_{ik} = \sum_{h \in J_{ik}^+} w_h > p$$

A D_{ik} discordance index is also constructed, the calculation of which is relatively more elaborate. To identify D_{ik}:

- calculate all the weighted deviations between the attribute values for the two alternatives, i.e. calculate, for each attribute A_j, the quantity

$$w_j \, |x_{ij} - x_{kj}|$$

- the largest of these rejects can be identified

$$\max_j w_j \, |x_{ij} - x_{kj}|$$

- the largest of the attributes rejects in J_{ik}^-

$$\max_{j \in J^-} w_j \, (x_{kj} - x_{ij})$$

- the ratio between these last two quantities is calculated by placing

$$D_{ik} = \frac{max_j \, w_j \, |x_{ij} - x_{kj}|}{max_{j \in J^-} \, w_j \, (x_{kj} - x_{ij})}$$

The D_{ik} index test is carried out based on the parameter (q), i.e. you want $D_{ik} < q$. This means that the differences in the various attributes between the two decisions can not be relatively small compared to those where it is better than d_k.

If in the comparison between d_i and d_k, both tests are passed, it is said that d_i is preferable to d_k and the recent decision can be eliminated.

Usually, the values p = 0.7 and q = 0.3 are set respectively: it is evident that the test becomes more difficult to pass when increase (p) and decrease (q), risking not to detect any decision to eliminate.

Other variants of the ELECTRE method take into account other psychological aspects in the evaluation of the alternatives. In particular, the fact that if, when comparing two decisions, the value of an attribute does not differ by more than a certain amount, then the two decisions are perceived as indifferent: this fact also reduces the possibility of establishing a ranking among the available alternatives and therefore tends to increase the number of "no-dominated" decisions.

In conclusion, the following advantages of this method can be listed[35]: it allows the use of fuzzy analysis, accepts qualitative and quantitative criteria, and has a multidimensional nature. Furthermore, the differentiated use of the two matrices of concordance and discordance allows both effects to be analysed independently and then combined further. The negative aspects of this method are the absence of an axiomatic basis, the difficulties in understanding it, due to the principles used to determine the concordance and discordance matrices. Finally, the thresholds are often set according to the opinion of the decision-maker, which therefore introduces a subjectivity factor.

PROMETHEE The method "Preference Ranking Organisation METHod for Enrichment Evaluation", called by the acronym PROMETHEE, was introduced by Brans and Vincke in 1985[36] and belonged to the category of higher-ranking methods. It introduces concepts and parameters that pose some physical or economic interpretations easily understandable by the decision-maker.

The method involves comparisons between two alternatives and then calculates the difference by applying one of the six "transfer functions" (Figure 72).

35 Munier, N., 2011. *Ibid.*

36 Brans, J.P., Vincke, Ph., 1985. A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). Management Science 31, 647–656.

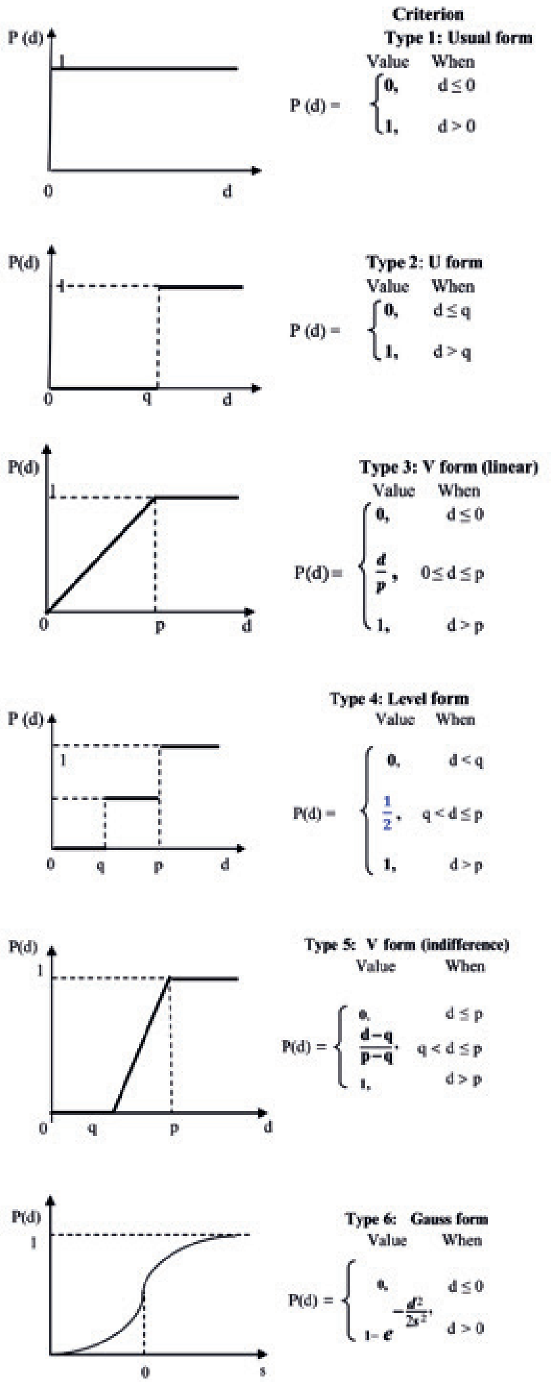


Figure 72 Transfer functions of the PROMETHEE method (Munier 2011).

A precondition is that the different alternatives are comparable. For a given criterion "I", and considering two alternatives "a" and "b", the difference between them will be equal to the difference in their scores, that is:

$$d_i\ (a,b) = v_i\ (a) - v_i\ (b)$$

Using this value in any of the transfer functions is possible to find a value between 0 and 1, i.e.

$$0 \leq P_i\ [d_i\ (a,b) \leq 1$$

This procedure applies to each criterion and can, of course, be a maximisation or a minimisation criterion. In the transfer functions (Figure 72), the parameter "q" is the indifference threshold. This level of indifference identifies which is the most significant value of the difference where "a" is indifferent to "b". There is also another parameter "p" which identifies the minimum value of the difference where "a" is indifferent to "b". For example, if the difference between "a" and "b" is 0.3 and the level of indifference is 0.45, "a" and "b" are considered indifferent. However, if this difference is greater, also this value is greater than the level of preference, a>b.

In the PROMETHEE method, therefore, it is necessary to use an evaluation table to establish the weights for each criterion, select the transfer function for each criterion, and finally set thresholds. The choice of the transfer function to adopt is fundamental and returns different values. Therefore, for each criterion it is necessary to select the optimal function: for example, for a criterion with high uncertainty, it is convenient to use the Gaussian function or where the difference is a direct relationship with the quality, for example, it is convenient to use the linear function. In this method, there is also a high subjectivity content, which manifests itself in the selection of the transfer function and the setting of the levels of indifference "q" and preference "p".

There are different versions of PROMETHEE, and each is built with a specific purpose. Very generally:

- PROMETHEE I: It performs a partial ranking of alternatives as it only considers those where there is a strong preference and does not compare conflicting alternatives.
- PROMETHEE II: Provides a complete ranking of alternatives, which is based on a net result of positive and negative flows. This version uses sensitivity analysis to know the stability of solutions when some parameters change, e.g. criteria weights.

- PROMETHEE III: Works with higher-ranking evaluated relationships and also with fuzzy logic problems.
- PROMETHEE IV: Used when there are many alternatives.
- PROMETHEE V: Applies full linear programming to select alternatives previously identified by PROMETHEE II and subject to several restrictions.

The calculation sequence for the PROMETHEE model consists of the following steps:

- prepare a decision matrix with alternatives in rows and criteria in columns;
- assign a weight to each criterion and select a transfer function for each of them;
- establish preference thresholds (p and q) and indicate whether this is maximization or a minimization criterion;
- start working in the first column with the first two alternatives (i.e. the first two rows) by analysing the difference between the values of two alternatives in that column. Compare this difference with the thresholds and apply the corresponding formula for the selected transfer function. Then multiply this value by the weight attribute assigned to this criterion;
- at the end of the first row, add all the values obtained;
- define a square matrix or index matrix of preference, with alternatives such as rows and columns. Assign a zero at the intersection of the same alternative in a column and in a row. Then, put in each cell the value found in the previous step;
- the procedure is repeated for alternative pairs;
- once completed, add the values in each row and then calculate their average (remember to divide by the number of alternatives minus one, because always one of the values is zero). This average indicates the average positive flow, i.e. one that corresponds to the alternatives that generate it. Do the same for each column, which is the average negative flow because it corresponds to the alternatives that receive it;
- since an alternative usually generates and receives flows, the difference between them evaluates its value. The larger value of these differences signals the first alternative in the ranking, and the balance of the decreasing values allows the ranking order of the alternatives;
- the sensitivity analysis for the criteria takes place through the variation of the thresholds.

In conclusion, we can say that the PROMETHEE method is logical and rational and that everyone can understand and use it. Moreover, it allows easy and direct comparison of a pair of alternatives concerning a criterion and the transfer functions allow the analyst to consider the type of data available. However, this method has the disadvantage of having a high component of subjectivity in establishing the weights of the criteria, the parameters "q" and "p" and in estimating which transfer function to use.

AHP The Analytic Hierarchy Process (AHP) method, prevalent and used in various fields, was proposed by the American mathematician Thomas Saaty in the 1970s. AHP is a process that allows giving the various alternatives a weight that represents their relative effectiveness in achieving the final goal. This is not further specified, but it is implied that it is the maximum satisfaction of the decision-maker.

In the AHP, it is assumed that in the decision-making process, the decision-maker is faced with elements of judgement organised in at least three levels: these elements are represented by nodes of a graph arranged on as many lines as there are levels (Figure 73). At the upper level a single node, representing the objective, appears, while at the lower level alternatives appear. In the intermediate levels, the characteristics to be taken into account in the decision-making process appear: in the simplest case, there is only one intermediate level and the attributes appear in it.

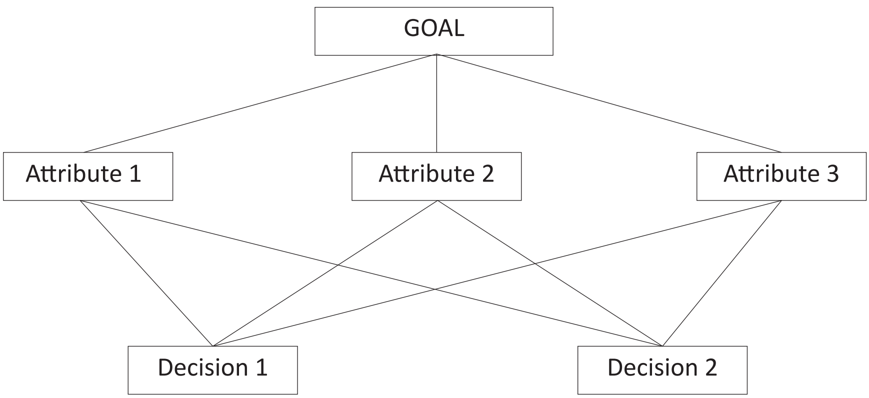


Figure 73 Schematisation of the decision-making procedure using the AHP method.

Each element of a level has an "influence" on all other parts of the elements of the next higher level. The existence of this influence is expressed by an arc (segment). The magnitude of the influence is mainly a weight associated with the arc, which is determined from time to time by systematically using one of the techniques for determining weights.

In this method, the values of the attributes, even if they are quantitative, are not relevant. The critical aspect is the comparison of the effectiveness between each element of the same level and the other ones of the upper level.

In essence, in order to formulate the problem and obtain an operational indication, in the case of two decisions and three attributes, the decision-maker must answer a series of questions as follows:

- how important is each attribute more or less important than the others in achieving the objective?
- for each of the three attributes, how much is the first decision to be considered more satisfactory than the other ones about the specific attribute?

Segments that link different elements of a (lower) layer to the same element of an immediately higher layer, as mentioned above, are given numerical values that are called priority values. These express the normalised importance of the elements of the same layer to the linked ones on the higher layer. For example, if we attribute values to the first levels of the example in Figure 73, we will obtain in Figure 74 that the first element of the lower level is twice more effective than the third element and six times more effective than the second in achieving the characteristics of the element indicated in the upper level. To arrive at the optimal solution, we must choose at the lowest level the best alternative for achieving the objective at the top of the hierarchy. Ultimately, what is suggested in the AHP is to calculate, for each alternative, an specific index. It is calculated by the sum of the products of the priorities, along paths connecting alternatives to the objective.

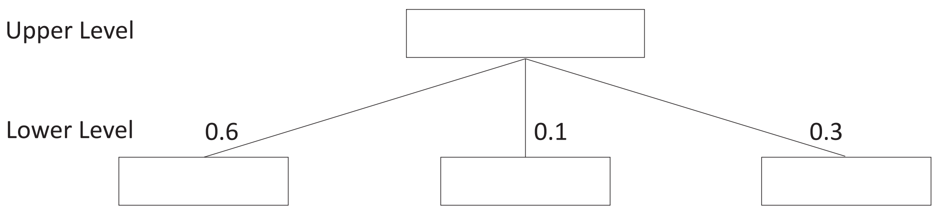


Figure 74 Example of attribute priority in the AHP method.

The AHP method is among the most used because of its intuitiveness and ease of use. However, it is also clear that in this method, there is the subjective component due to the choice of the preference of the criteria, and therefore if a problem is submitted to two different people, although the same method is used, different results can be obtained. Another disadvantage is that it is slow and can discourage the decision-maker if there are a large number of criteria and, therefore, also comparisons to be made.

TOPSIS The TOPSIS method, which stands for Technique for Order Preference by Similarity to Ideal Solution, is a technique for sorting preferences by proximity to a fictitious utopian solution, which is called the ideal solution. At the same time, distance from the “worst-case” or another fictitious solution, called the “negative ideal”. The (fictitious) ideal solution, also more explicitly called “positive ideal”, is constructed by taking from a table decision attributes, for each attribute, the highest value. Conversely, the negative ideal solution is constructed by taking the worst values of all attributes. If there are two attributes, the situation can be exemplified as Figure 75.

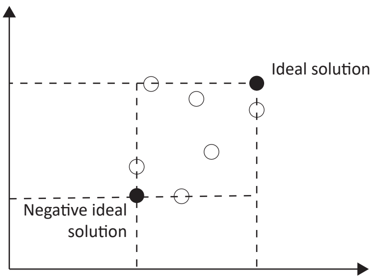


Figure 75 TOPSIS positive ideal and negative ideal solutions.

Now indicate with s_i^+ the deviation or distance of the i-th alternative from the positive ideal solution and with s_i^- the distance from the negative ideal solution (Figure 76).

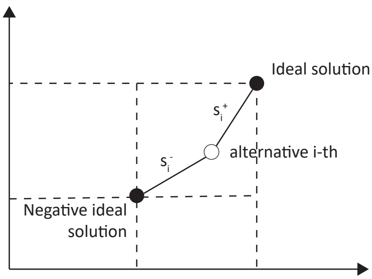


Figure 76 TOPSIS calculation of the distance between alternative and positive ideal and negative ideal solutions.

Calculate the value of the i-th decision $v_i = v(d_i)$ as:

$$v(d_i) = s_i^- / (s_i^+ + s_i)$$

Therefore, the value of a decision is the greater the distance from the ideal negative solution and the smaller the distance from the ideal positive solution. In practice, two elements have to be taken into account: the different weights of the attributes and the need that the scales of their measurement do not affect the result by distorting it. The latter aspect is avoided if the values of the attributes are normalized in some way. In any case, the distances should be properly weighed.

In conclusion, it can be noted that this method has the disadvantage of not having thresholds. However, in its favour it can be said that: it is straightforward to understand due to of its simplicity and rationality; it can even be solved manually for small problems without too much effort; besides setting the weights for the criteria, it is one of the methods on which subjectivity has the least influence; finally, it gives an idea of “optimum”.

4.3.2 Multi-Objective Decision Methods

MODM methods, as the name suggests, are used in decision-making processes in which several objectives, even conflicting ones, must be achieved simultaneously. The characteristics of MODM are a set of objectives and a series of well-defined constraints. In this type of method to address optimization problems, two main difficulties can be highlighted: compromise and scale problems that complicate MODM problems through the mathematical programming model.

The first type of problem is usually given a final optimal solution through the use of mathematical programming that allows to transform several objectives into a single weighted target. Therefore, it is necessary to identify and insert a process to obtain compromise information between the objectives considered.

On the other hand, The second type of difficulty is related to the size of the problem and its computational cost. Many evolutionary algorithms have been developed to del with those problems, such as genetic algorithms, genetic programming, and evolutionary strategy[37].

37 Rechenberg, I., 1973. Evolutionsstrategie; Optimierung technischer Systeme nach Prinzipien der biologischen Evolution. Frommann-Holzboog, Stuttgart-Bad Cannstatt.

Two salient dates in the historical development of MODM methods are 1951 with the publication of Kuhn and Tucker[38] introducing the concept of vector optimization and 1973 with Yu's proposal[39] of the compromise solution method to address the problems of MODM. Following these publications, considerable progress has been made in the development of these methods and their application in various areas, such as transport planning, business management, and investment selection funding or land use planning, and water management.

The evolution of MODM methods and the combination of all methods developed before the 1990s, has made it possible to deal with the most complicated problems in the real world, moving from simple multi-objective programming to multi-level multi-lens and multi-stage multi-objective programming (Figure 77). Moreover, if fuzzy variables are also included, more huge problems can be tackled, as suggested by Bellman and Zadeh in 1970[40]. The use of fuzzy multi-obectives linear programming (FMOLP) allows generating a sharp solution that has the highest degree of adherence in the decision set.

Finally, another factor that has led to exstensive use of these methods is that MODMs ignore the problem of subjective uncertainty, which is very present in MADMs.

Among the many algorithms and methods belonging to the MODM category, in the next pages, the genetic algorithms (GA) will be presented. Genetic Algorithms are the translation of the biological concept of evolution. Together with neural networks[41] and fuzzy logic, GA constitutes the three main branches of classical computational intelligence[42]. Genetic Algorithms are widely used because they are excellent methods for the optimization of problems with difficult characteristics and are very flexible and, therefore, applicable to a wide range of optimization problems.

38 Kuhn, H.W., Tucker, A.W., 1951. Nonlinear programming. In Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability, 481–91. Berkeley: University of California Press.

39 Yu, P.L., 1973. A Class of Solutions for Group Decision Problems. Management Science 19, 936–946. https://doi.org/10.1287/mnsc.19.8.936

40 Bellman, R.E., Zadeh, L.A., 1970. Decision-Making in a Fuzzy Environment. Management Science 17, B-141. https://doi.org/10.1287/mnsc.17.4.B141

41 Rosenblatt, F., 1958. The Perceptron: A Probabilistic Model for Information Storage and Organization in The Brain. Psychological Review 65–386.

42 Kramer, O., 2017. Genetic Algorithm Essentials, Studies in Computational Intelligence. Springer International Publishing. https://doi.org/10.1007/978-3-319-52156-5

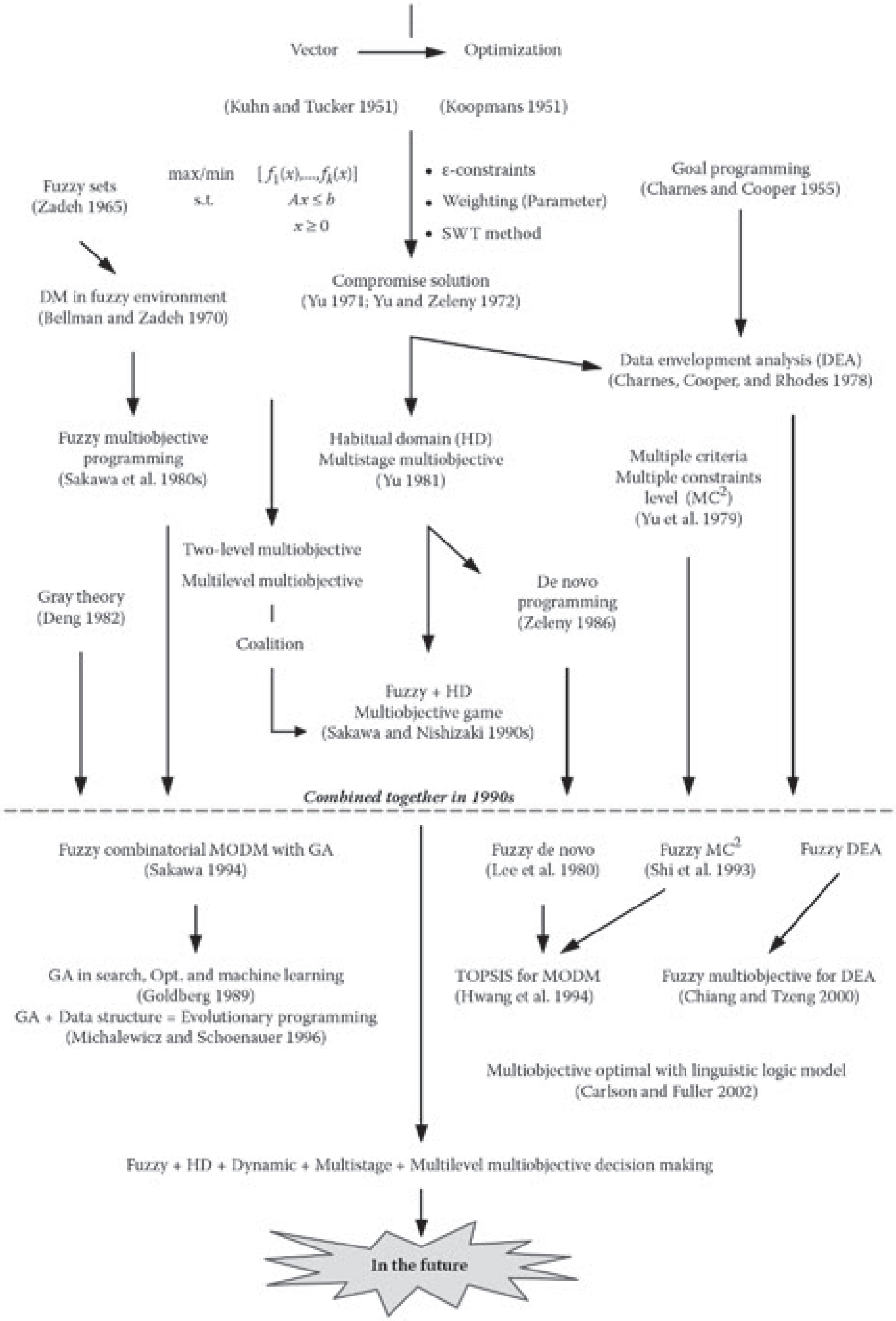


Figure 77 Outline of the development of MODM methods (Tzeng and Huang 2011).

Genetic Algorithm Genetic algorithms are optimization methods inspired by the concept of evolution in biology. Charles Darwin[43] was the first who proposed the concept of evolution[44] as an explanation for the biological development of species through the selection and survival of the strongest. The coding of the characteristics of each creature is contained in the DNA. It is also the basis of evolutionary processes. The evolution of species is the result of an optimization process that has clearly been successful and has been underway for four billion years.

The development of algorithms able to replicate the evolution process started in the sixties and led to the generation of four main flows of variants of the Genetic Algorithm: genetic algorithms, evolution strategies, evolutionary programming, and genetic programming.

One of the variants in advanced artificial systems was developed in Europe by Ingo Rechenberg and Hans-Paul Schwefel, who gave it the name "evolution strategies"[45]. This type of genetic algorithm is still very much used in research because of the possibility of having continuous spaces of solutions. In the same years, John Holland introduced genetic algorithms as optimization methods in the United States[46].

The first genetic algorithms were mainly based on representations of binary strings. In order to map the genotypes of this string, a decoding function was needed. Moreover, in the beginning, the crossover operation played a more important role than that of mutation, which consisted of a simple mutation of the bits transforming the zeros in one and vice versa with a fixed probability.

Later, Fogel, Owens, and Walsh introduced "evolutionary programming"[47], originally designed to conduct optimization processes that could accept a set of strings as input. Later, this type of evolutionary programming was extended for optimization also in binary and continuous solution spaces, also equipped with mutation techniques. Finally, we arrived at the "genetic programming" that has currently evolved into "Machine Learning".

43 Charles Robert Darwin (1809 - 1882) was an English naturalist, geologist, and biologist, best known for his contributions to the science of evolution.

44 Darwin, C., 1859. On the Origin of Species. John Murray, London.

45 Rechenberg, I., 1978. Evolutionsstrategien, in: Schneider, B., Ranft, U. (Eds.), Simulationsmethoden in der Medizin und Biologie, Medizinische Informatik und Statistik. Springer, Berlin, Heidelberg, pp. 83–114. https://doi.org/10.1007/978-3-642-81283-5_8. Schwefel, H., 1977. Numerische Optimierung von Computer-Modellen. Birkhäuser, Basel.

46 Holland, J., 1992. Adaptation in Natural and Artificial Systems. Reprint MIT Press. Massachusetts, United States.

47 Fogel, L.J., Owens, A.J., Walsh, M.J., 1966. Artificial Intelligence through Simulated Evolution. John Wiley & Sons.

Over the years, all these four variants have grown together. They also have influenced each other to the point where it is difficult to distinguish them today. Most of the concepts, representations, and mechanisms have been introduced in all the variants, and today we talk generically about Genetic Algorithms.

In order to proceed with the study of the functioning of the genetic algorithms, it is possible first of all to schematize the evolutionary processes as a continuous cycle, in which all the critical concepts of GA appear (Figure 78). The cycle begins with an initially random or manually established population and then proceeds recombining two or more solutions with the crossover operator. From this operation, we obtain changed solutions, among which, through a fitness function, the best solutions for the next generation are selected. Finally, the evolutionary cycle ends, and then, if it is still the case, restarts and continues the race of genetic optimization. Below all the steps are shown in detail and some of the main features of GA.

Initialization The first step of the resolution process through the genetic algorithms is to identify and select the individuals that form the mating pool to which the crossover operators will be applied.

The classical genetic algorithm manipulates populations of chromosomes, which are represented by strings of solutions for a particular problem. A chromosome is the abstraction of a biological DNA chromosome, which can be thought of as a string of letters of the alphabet. Classical representation involves the use of bit

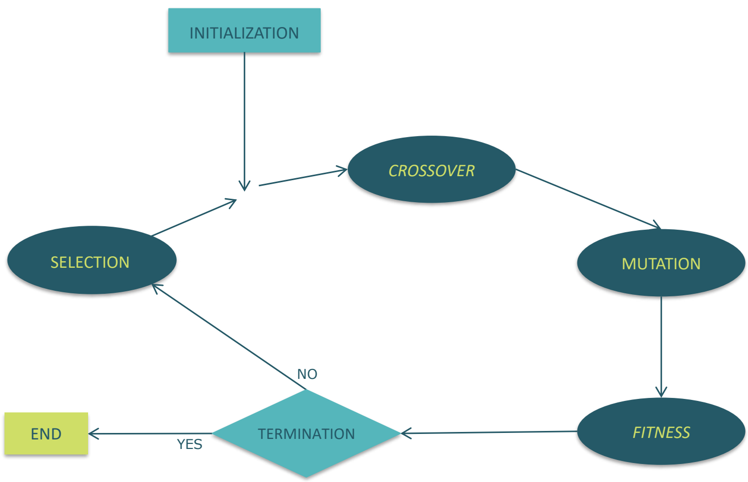


Figure 78 Genetic Algorithm cycle of initialization, crossover, mutation, fitness computation, selection, and termination.

strings of an average length of 10 elements, such as 1001001001. Each solution contained in this set of strings is a potential candidate for optimization of the problem, and therefore its inclusion in the initial pool plays an important role.

The problems in which GA, the solution sets, are usually used, even if they are finished, are so big that the evaluation of all possible solutions is not computationally feasible. It is not uncommon that, for example, a GA that operates on bit strings of length 100, then returns a solution space of 2100-1030 individuals.

Crossover The operation of crossover is used to select the individuals of the generation of the parents and to combine the genetic material of two or more solutions to obtain new individuals.

In nature, most species have two parents, except for some exceptions in which there are no distinctions between the sexes, and therefore, they have only one parent. Instead, with GA, it is possible to apply the crossover operators to more than two parents.

The mechanism triggered by the crossover operators in the genetic algorithms is based on the mixing of the genetic material of the parents, subdividing the bit strings into n points. For example, two strings can be subdivided into two portions and then be reassembled alternatively to generate new individuals (Figure 79).

This type of operation makes it possible to combine parts of strings that could represent successful solutions and which, if combined, also exceed the performance of their parents.

There are many alternative forms of crossover operation. The one-point, two-point, or multi-point crossover. In this way, it is possible to choose a sequence of crossover points along the length of the chromosome and then generate new strings from the two parents exchanging at each crossover point. There is also the dominant crossover, which then chooses each component from one of the parental solutions. Alter-

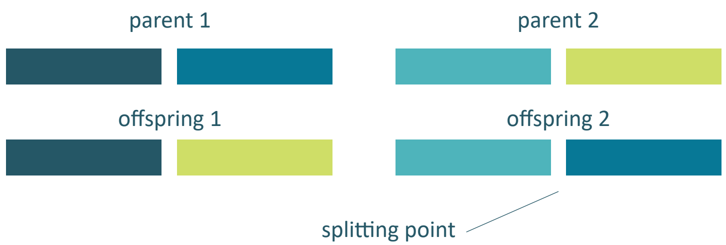


Figure 79 Illustration of one-point crossover that splits up the genome of two solutions at an arbitrary.

natively, the uniform crossover that uses a fixed mixing ratio, such as 0.5, to choose a bit from either parent randomly. Finally, the algorithms also differ concerning the creation of one or more children from the operation of the crossover.

Mutation The process of mutation alters one or more genetic values of an individual compared to its initial state, with the result that new individuals are generated who will be able to help find a better solution than before. The mutation disturbs the solutions, through random changes, also avoiding that the population stagnates at any local optima. The strength of this disturbance is called "mutation rate".

Mutation operators must meet three main requirements:

- The first one is the reachability of each point from an arbitrary point in the solution space. An example that may complicate the fulfilment of this condition is the existence of constraints that restrict the entire solution space to a feasible subset. There must be a minimum possibility of reaching every part of the solution space; otherwise, the possibility of finding the optimal is not definite.
- The second one is impartiality. The mutation operator should not induce drift in a particular direction.
- Finally, the third is scalability. Each mutation should offer a certain degree of freedom and adaptability. This is usually possible for operators of mutations that are based on a probability distribution. For example, for the Gaussian mutation, which is based on the Gaussian distribution, the standard deviation can scale randomly drawn samples across the entire space of the solution.

The implementation of mutation operators depends on the representation used. As already mentioned, for example, in the case of bit strings, the bit flip mutation is usually used, which changes a zero bit to one bit and vice versa, with the mutation rate chosen according to the length of the representation. Instead, if the representation is a list or a string of arbitrary elements, the mutation randomly chooses a substitute for each element. This mutation operator is known as "random resetting". Finally, the Gaussian mutation is the most popular operator for continuous representations, which is also capable of satisfying all three of the above conditions. It is arbitrarily scalable, all regions in continuous solution will be reachable, and thanks to the symmetry of the Gaussian distribution, it does not prefer any direction and therefore is not drifting.

Genotype-Phenotype Mapping An operation not always required is genotype-phenotype mapping. After the crossover and the mutation, the new population of descendants must be evaluated concerning its ability to solve the problem optimization. Depending on the representation a mapping of the chromosome, called genotype, and the real solution, called phenotype, is necessary. This process of genotype-phenotype mapping should avoid introducing bias. An example of prejudice occurs when mapping takes place over most of the genotype space but only over a small set of phenotypes.

Fitness The "fitness" function allows measuring the quality of the solutions that the genetic algorithm has generated. The design of the fitness function is a relevant part of the modeling process of the entire optimization approach.

Dealing with a single target problem, it is easy to determine whether one solution is better or worse than another. Using a fitness function or fitness landscape in which a high value corresponds to a good solution, the solver aims is to find the maximum value assumed by the fitness function that will represent the best available design solution. Figure 80 shows a graphical display of a fitness landscape function for a problem with two variables and a single target. In the case of multiple objectives to optimized at the same time, the values of the fitness function of every single objective can be aggregated, for example, by calculating the weighted sum.

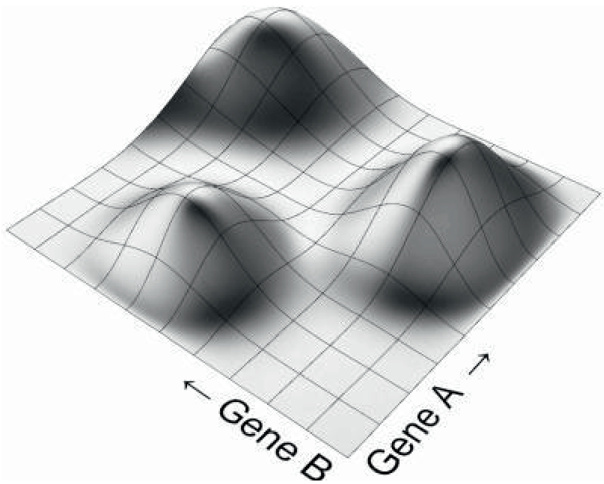


Figure 80 3D representation of a fitness landscape of a two-variable model. The highest peaks of the landscape are the most desirable design solutions. (David Rutten)

The performance of a Genetic Algorithm is usually measured in terms of the number of fitness function evaluations required until the optimal solution is found or approximated to the desired accuracy. Most approaches, therefore, aim to minimize the number of calls to fitness functions, thereby also reducing time.

Selection The selection phase allows identifying the best solutions generated so that they become optimal parents for the new generation. The selection mechanism for choosing the parents of the new generation is akin to Darwin's principle of survival of the fittest. It is a process that allows converging towards optimal solutions, discarding some of the solutions generated based on the fitness values of the population. In the case of minimisation problems, low fitness values are preferred and vice versa in case of maximisation problems.

Many selection algorithms are based on randomness. The "fitness proportional selection" selects parental solutions randomly with uniform distribution. The probability of being selected depends on the suitability of a solution.

Then there are elite selection operators who select as parents the best solutions of the offspring's solutions. "Comma selection" selects the best μ solutions from among the solutions of the offspring λ. While the "Plus selection" selects the best μ solutions from the λ offspring and the old μ parents that led to their creation.

Both in the case of "Comma selection" and "fitness proportional selection", good parents can be forgotten. Although this may seem counterproductive to the optimization process at first, it may be a reasonable strategy to overcome local optimization.

Another famous selection operator is the one called "tournament selection", where a series of solutions are randomly selected, and within this subset, the best solutions are finally selected as new parents. This type of selection offers a positive probability of survival for each solution, even if it has worse fitness values than other solutions.

Termination In the last step, the condition that ends the main evolutionary cycle occurs. Often the genetic algorithm proceeds for a predefined number of generations the time and cost of the fitness function can limit the duration of the optimization process. A further useful termination condition is the convergence of the optimization process. As the optimal approaches, the progress of the fitness function improvements can decrease significantly. If no significant process is observed, the evolutionary process stops because the result has been achieved, or sometimes stagnation problems have occurred. The latter condition may occur, for example, when using the optima of continuous optimization problems and there is no difference in subsequent generations after applying the fitness function.

Stagnation can only mean that the search may have been stuck in the local optima, thus missing the global optima. If the genetic algorithm is starting from different areas and always approach the same space of the solution, the local optimum is likely a great attractor rather than finding a better local optimum than the global one.

Constraints One of the main characteristics of optimization processes is the presence of one or more constraints that allow reducing the space of the solutions (Figure 81). Constraints can be of different kinds: they can be, for example, mathematical restrictions, logical constraints, physical conditions, execution time limits, etc. The result may be that a solution is not applicable because it is not feasible.

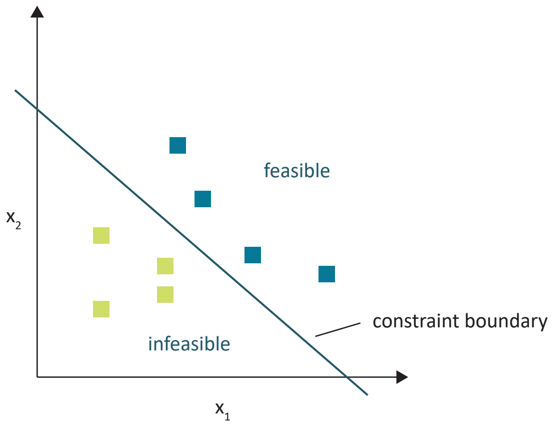


Figure 81 Illustration of solution space with one linear constraint that divides the solution space into a feasible and infeasible part.

Constraints in Genetic Algorithms can be implemented through a constraint function that limits the space of the feasible solution. For example, in continuous solution spaces, constraints can be formulated as equations and inequalities.

The use of the constraint function in optimization processes is a similar mechanism to the fitness function to achieve the optimal solution. Also, in this case, considering the different uses of the function, different scenarios can be prefigured: the calls of the function could be inexpensive or expensive. In the first case, several feasible solutions can be generated, which can then be verified later. In the second case, however, to reduce the number of uses of the constraint function, it is worth introducing mechanisms and techniques that significantly reduce the number.

The main techniques are:

- The death penalty, one of the simplest methods of dealing with constraints, is not among the most efficient. It consists of a code that requires genetic operators who are forced by the death penalty to generate feasible solutions.
- The penalty function consists in reducing the suitability of feasible solutions so that they will be less attractive and will not be selected for the creation of the new generation.
- Repair is a technique that allows turning unworkable solutions into feasible ones.
- The "decoders" allow to map the space of the captive solutions and transform it into a non-captive space or at least with less severe conditions.
- "Premature Stagnation" often occurs in case of space conditions of solutions with a low probability of success. The reason is mainly a significant decrease in mutation rates. To avoid premature stagnation, numerous strategies can be employed, such as mutation operators able to adapt to the shape of the constraints.

Pareto-front The problems of multi-objective optimization, as mentioned above, concern two or more conflicting objectives. That is the condition when a situation improve in one objective, at least in other ones deteriorates. It is, therefore, challenging to solve the problem because there is no unambiguous comparison between optimal solutions, as can be done when there is only one objective.

The challenge in multi-objective optimization is to find a set of solutions that are a compromise between all lenses. The goal is to generate a set of solutions that are not dominated by other solutions and therefore are not worse in all objectives. This set or set of solutions is also known as the "Pareto-set". The fitness values of the solutions in a "Pareto-set" build the "Pareto-front".

The key to the evolution of a Pareto-front with multi-objective Genetic Algorithms is the selection operator. Most selection operators are based on two phases. The first step is usually "non-dominated sorting", which sorts the solutions by domain level. The second step is based on non-dominated sorting and optimizes a secondary criterion, mostly aimed at spreading solutions across the whole Pareto-front (Figure 82).

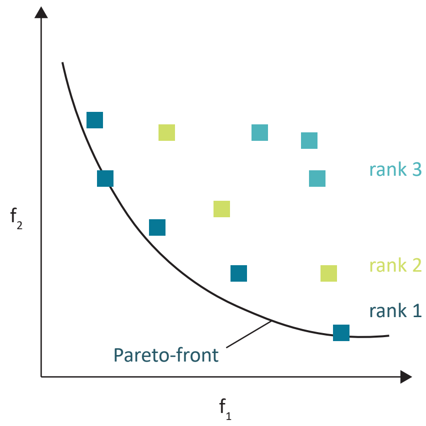


Figure 82 Non-dominated sorting sorts all solutions concerning their non-domination rank. The non-dominated solutions are closest to the Pareto-front in comparison to solutions of higher rank.

The phase of identifying undominated solutions is fundamental because a solution is "Pareto-optimal" if it is not dominated by any other solution in the solution space. Figure 83 shows the graphic representation of a solution for a problem with two objectives, in which space is divided into four quadrants. The Pareto-optimal is the set of all solutions that are not dominated in the entire solution space.

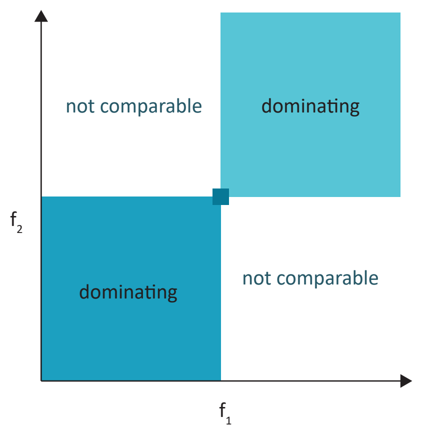


Figure 83 With two objectives for a minimization problem, a solution divides the space into four quadrants.

The three main secondary selection criteria used are:

- **Non-dominated Sorting Genetic Algorithm (NSGA)**
  It is a multi-target selection Genetic Algorithm widely used, and even its next version, NSGA-II, has been even more successful. It is a selection technique that is based on a non-dominated sorting and searches among non-dominat-

ed solutions those with a broader distribution. The algorithm then evaluates and calculates the "crowding distance" (Figure 84) for each solution and finally selects those with the most significant distance.

- **Rakes**
  Rake selection is an approach to maintain a uniform spread of solutions. It is similar to the NSGA-II because it is based on non-dominated solutions, and the solutions closest to the parallel lines are selected from among them (Figure 85). The rake lines are placed by equally dividing the space between the extreme solutions, i.e. those with the best suitability for each target. For each line, the closest point is selected among the solutions with rank one. If the number of undominated solutions is too small, the solutions of the next rank can participate in this selection process. The rake approach works best for Linear Rank solutions.
- **Hypervolume Indicator**
  This technique makes it possible to approximate the Pareto-front, measuring the area in the solution space, which is dominated by a population. Considering a reference point dominated by all solutions, the hypervolume dominated can be calculated. In Figure 86, the hypervolume is highlighted in light blue, and in blue, the contribution of a single solution generated subsequently.
  The calculation of the hypervolume can become a complicated task for more than two objectives. In particular, in the case of many objectives, volumes often overlap and are not easy to calculate. In addition, selecting the best solutions that maximize hypervolume is a matter of combinatorial optimization.

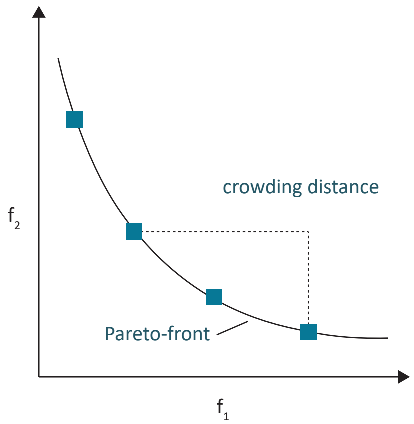


Figure 84 Illustration of crowding distance.

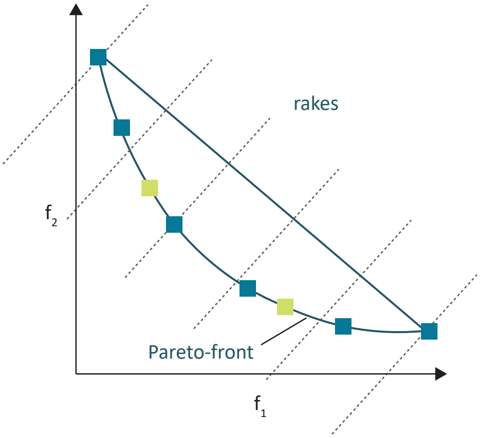


Figure 85 Illustration of rake selection.

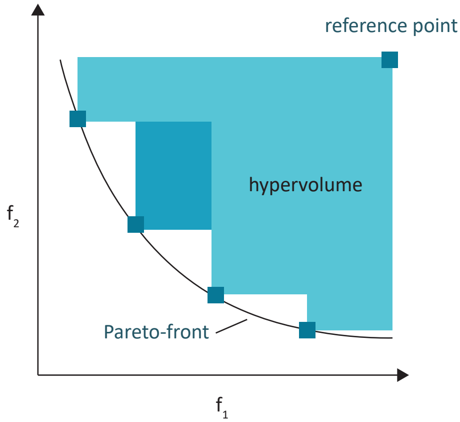


Figure 86 Illustration of a Genetic Algorithm that maximizes the dominated hypervolume in objective space.

5 PURPOSE IN ACTION

Sustainability, digitization, and optimization, the three key topics of the thesis, are combined in this chapter. From each of them, some aspects and tools are selected to put the objective of the thesis into practice. From sustainability derive the design objectives, from the new technologies introduced by digitization Building Information Modeling was chosen and from optimization derive the processes and methods for solving complex design problems.

All these elements will be combined to develop the replicable methodology proposed for the optimization of the building's design process (section **5.3**). Some examples of the procedure developed will then be reported to show its possible uses for different objectives, digital models, tools, and calculation methods (section **5.4**).

The first two paragraphs, on the other hand, concern some reflections and insights on the three starting topics.

Sustainability finds its place in Building Information Modeling in its 7D. Today's professional reality, however, is different. The framework on sustainability in BIM has been expanded through an empirical and qualitative study based on data collection through interviews with experts in the field. From the analysis of the data collected, some reflections presented in paragraph **5.1** emerged.

The interviews with experts were also an opportunity to highlight some differences in the perception and use of BIM, not only as a technological innovation for the construction sector but also as a revolution in the whole design process (paragraph **5.2**).

5.1 BIM and Sustainability

The seventh dimension of BIM is defined in the Italian standard UNI 11337-1 as: simulation of the work or its elements according to the sustainability (economic, environmental, energy, etc.) of the intervention, as well as space, time and production costs[1].

Building Information Modeling, thanks to its intrinsic characteristics and potential to generate a model updated continuously and increasingly faithful to reality, can, therefore, also be able to manage all aspects related to sustainability. Using BIM tools, it is possible to perform simulations and analysis of the performance of the sustainability of the building or even just some of its elements can be carried out: for example, it is possible to study multiple aspects such as orientation, shape, daylighting, energy profile, materials, etc.

In addition to the standard mentioned above, several references and images include the 7D dimension of BIM, such as the one in Figure 44 in paragraph 3.3 or many others that could be reported and quoted.

All these references, however, differ from reality if one considers, for example, the applications available to professionals. Figure 87 shows the most widely used software, subdivided by the different levels of evolution of BIM and its dimensions.

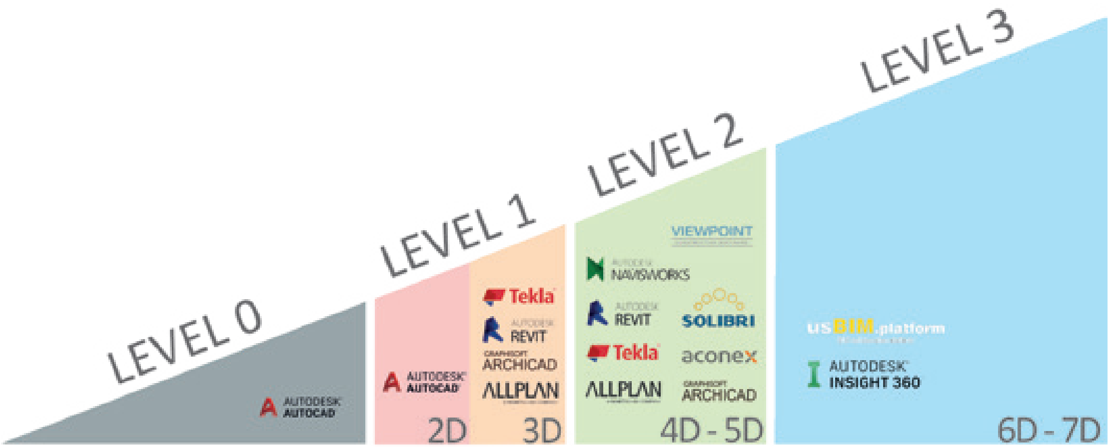


Figure 87 Most common tools available and used for each BIM levels and dimensions.

1 UNI 11337-1:2017. *Ibid.*

2 AutoCAD is a commercial computer-aided design (CAD) and drafting software application. Developed and marketed by Autodesk,[1] AutoCAD was first released in December 1982 as a desktop app running on microcomputers with internal graphics controllers.

In level 0 and for 2D, the most widespread tool is AutoCAD[2]. Although there are also other similar and opensource tools, AutoCAD is the most used by architects, project managers, engineers, designers, graphic designers, urban planners, and other professionals.

The most common tools for 3D geometric modeling, corresponding to a BIM Level 1, and certified by buildingSMART are: Archicad[3], Revit[4], Tekla[5] and Allplan[6].

In Level 2, there are several tools to manage relatively new aspects of BIM. The list is continuously updated. However, those that are more widespread and consolidated in professional firms for collaboration, coordination and model-check using BIM are Navisworks[7], Solibri[8], and BIMcollab[9]. Synchro[10] and Assemble System[11] are more specific for 4D and 5D dimensions.

3 ARCHICAD: architectural CAD BIM software for Macintosh and Windows developed by the Hungarian company Graphisoft. It offers digital solutions for the management of all common aspects of aesthetics and engineering during the entire design process of the built environment. After its launch in 1987, with Graphisoft's "Virtual Building" concept, ARCHICAD has been considered by some as the first implementation of BIM.

4 Autodesk Revit is building information modeling software for architects, landscape architects, structural engineers, mechanical, electrical, and plumbing (MEP) engineers, designers, and contractors. The original software was developed by Charles River Software, founded in 1997, renamed Revit Technology Corporation in 2000, and acquired by Autodesk in 2002.

5 Tekla Corporation: Finnish company specialized in CAD and BIM design software in the building, infrastructure and energy sectors. The name Tekla is the abbreviation of the Finnish word Teknillinen laskenta, which means technical computation. The company is known for its main product Tekla Structures, initially Xsteel, a BIM and CAD program for 3D modeling and details in steel and concrete structures that allows following the development of the project and individual elements during all phases of development.

6 Allplan is a BIM software from the company Nemetschek Allplan Systems GmbH with headquarters in Munich. The first version was presented in the 1980s by Professor Georg Nemetschek. In 2006 Nemetschek acquired Graphisoft, a manufacturer from Archicad.

7 Navisworks is a tool used primarily for 3D design review. Navisworks allows users to open and combine 3D models, navigate around them in real-time (without the WASD possibility) and review the model using a set of tools. It also includes some plug-ins for 4D and 5D simulation. Sheffield created the software, but in 2007 it was purchased by Autodesk for $25 million.

8 Solibri, Inc. develops and markets Quality Assurance solutions for AECO field that improve the quality of Building Information Modeling (BIM). Solibri Model Checker is a tool for BIM validation, compliance, coordination, design review, analysis, and code checking.

9 BIMcollab is a tool for collaboration platform built on IFC and BCF open standards to store, share, and solve issues with history tracking. BIMcollab® is a brand owned by KUBUS BV, a Dutch software company offering BIM solutions for Design & Build and is also an exclusive distributor for GRAPHISOFT and Gold partner of Solibri, Inc. in the Benelux.

10 Synchro Software, Ltd. provides digital construction software and services that improve the safety, reliability, predictability, and quality of complex construction projects. Their 4D digital construction platform serves the global market, combining traditional Gantt chart CPM scheduling with integrated 4D visualization capabilities in real-time. In 2018 Bentley Systems, Incorporated announced the acquisition of Synchro Software, Ltd.

11 Assemble Systems, an Autodesk company, provides tools for Manage BIM models, drawings & point clouds – perform design reviews, bid management, take off, change management, and estimating.

For BIM 6D and 7D Level 3, software like Green Building Studio[12] or the Italian us.BIM platform[13] could be mentioned, but due to their limited flexibility or the extremely recent development, they cannot yet be considered tools with a wide range of diffusion and use among professionals.

Another relevant factor not to be overlooked is the very association of sustainability and a specific dimension of BIM. It has been chosen to report the Italian definition that associates sustainability to 7D. Nevertheless, even a short online search shows that there is some confusion about it. The Italian BIM-7D is exchanged with BIM-6D in other contexts. This fact highlights even more how this level has not yet been reached, and this information is not yet fully managed in the building process in the BIM environment.

The framework on BIM and sustainability has been expanded through an empirical and qualitative study. It is based on data collection through a series of interviews with experts in the field. The aim is to understand how sustainability aspects are dealt with in the current 4.0 construction context and how the qualities of BIM are used to achieve sustainable development goals. Industry experts were interviewed to see if and how digital BIM models and their CDE change the collaboration and coordination of the different people involved in the construction process, particularly on aspects of BIM 7D.

In order to have different points of view, five people were selected who hold various roles concerning BIM and work in different contexts - companies, research centres, architectural or engineering firms - on projects from small to large scale. The interviewees are two architects, an engineer who is in charge of the MEP part[14], a researcher and coordinator of European projects, and a BIM manager.

The interviews conducted are semi-structured interviews for which a track has been developed to guide the conversation with the experts through the pre-established topics (e.g. personal role and responsibility, experience with BIM, tools used, sustainability, energy simulation, etc.). The guide for conducting the semi-structured interviews is available in the appendix. The interview guide was used during the conversation in a free and non-linear way to deal with all the pre-established

12 Autodesk® Green Building Studio is a cloud-based service that allows running building performance simulations to optimize energy efficiency.

13 usBIM integrates platforms, BIM tools and software specifically for building and construction: Developed by ACCA, a leading company in Italy in the development of software for construction, engineering ,and architecture. ACCA wins the buildingSMART International Award 2019 in Beijing in the Professional & Student Research category with the Structural E-Permit project.

14 Mechanical, electrical, and plumbing (MEP) refers to these aspects of building design and construction.

topics. At the sam time, the interviewee could dialogue freely and follow him/her reasoning in the areas on which he/she could provide further information.

All interviews started with some preliminary explanations about the purpose of the research, chosen people, and why his or her point of view and work experience are considered significant. The interview continued to address the three parts of the track:

- one concerning some general questions to frame the interviewee's professional profile;
- the second group of questions specific to Building Information Modeling
- Finally, a third part focuses on sustainability and energy aspects.

The interviews were recorded and then transcribed and translated for analysis. For this purpose, the Grounded Theory Method (GTM)[15] was used with an iterative approach of constant comparison between the data obtained from the interviews and the data present in the theory and bibliographical references studied[16].

5.1.1 Interviews Data Analysis

> «And then, just to tell it in a Greta Thunberg way, I see [BIM] as a process that allows you to conduct a reasoned design aimed at optimizing resources against waste [at the] construction site, encouraging a reduction in emissions. If I have more control upstream of the entire process, saving energy and conduct a correct and responsible design, […] then [BIM] represents an evolution of the designer's approach.» (Interview with architect, 23 07 2019)

The goal of this study was to see how our respondents thought about the relationship between BIM - a new type of information coordination and collaboration - and sustainability goals. The interviews allowed us to explore two main questions: 1) What are the different concepts about sustainability in digitized construction, and 2) how do current models reflect the use of these concepts by the different communities of practice who collaborate to achieve sustainability goals?

Each interviewee as evident on the need for reaching sustainability goals, but each has a different point of view on what needs to be done to facilitate the inclusion of these aspects in the building design process.

15 Glaser, B.G., Strauss, A.L., 1999. Discovery of Grounded Theory: Strategies for Qualitative Research, 1 ed. Routledge, New Brunswick. Lindlof, T.R., Taylor, B.C., 2010. Qualitative Communication Research Methods, Third edition. ed. SAGE Publications, Inc, Thousand Oaks, Calif.
16 Olson, J.S., Kellogg, W.A., 2014. Ways of Knowing in HCI. Springer-Verlag, New York.

Many elements influence the achievement of sustainability goals in a building project. The interviews revealed that there is a fundamental problem related to the sustainability and the "time" in which designers work on it. We interviewed a researcher who is an expert in European sustainable construction project, who phrased the challenge this way:

> «Why does sustainability come always after? The process is usually a kind of cascade process – something obviously that we notice in all the projects. Sustainability and energy are not a priority for users. So, they have some other priorities, so usually the designers also start with these and then, once something of the priorities of the users has been solved, then a kind of cascade effects start to calculate other things, calculating the compliant with energy regulations, … But it is something that comes after, always.» (Interview with researcher, 13 09 2019)

This problem of looking holistically at the environmental impact of the project was echoed throughout our interviews. The BIM manager explains the consequences of addressing the sustainability/energy aspects at the end of the design and building process, «So, at the end of the project you are only able to change the type of glass maybe, add some protections… so you have a small margin to modify the project» (Interview with BIM manager, 13 09 2019).

Creating a Common Data Environment across the design and construction team has the potential to help teams make choices with higer sustainability impact consideration. One of the obstacles to that in current practice is that BIM is used more commonly when the design process is relatively finished, and constructors and subcontractors coordinate the final mechanical design (MEP coordination) through the "clash detection" affordances of BIM modeling. However, our interviewees talk about how BIM could contribute to a lifecycle analysis of the sustainability of design and construction choices. Making sustainable design choices means designers and builders consider many aspects and are ready to make changes, adaptations, or modifications to the project to meet sustainability goals.

The BIM manager talks about one project which used sustainable elements and was pursuing LEED environmental certification but faced a challenge in passing off between building process and design process.

> «Now we are working on a huge project with a LEED certification, but the designers decided not to change the structural system because they want to be faithful to the design concept and to maintain the integrity of the original architectural design. So, the consequence was that in order to build the project, right to the original idea, we need a huge quantity of steel for the auxiliary structure, which in the end will … be thrown away. Sometimes we can make

decisions following a nice design and intense ideas…but behind the design in the construction site, the reality is quite different.» (Interview with BIM manager, 13 09 2019)

Not all coordination and collaboration problems are ones with environmental impact. However, there is a clear need to improve how designers use engineering and building expertise to assess the environmental impact of their design choices. In theory, BIM could help with this thanks to the advantage of being the building database and improved information exchange. However,for this to work for improved sustainability on design and construction projects, there needs to be clear ways to improve the choices about sustainability earlier in the project timeline. In theory, improvements to the project process brought about by BIM could create the possibilities for this kind of analysis earlier in the project.

There is a hope that earlier and improved access "data" would help with designing for sustainability. The researcher said:

«But there is a big gap on exploiting all this information and all these data ... It should be quite easy to integrate all these data and then to have a kind of tool that is able to exploit these data and to calculate some values or some indicators. In tha t way, it could also support the designer when they have to select options if Revit could put these indicators automatically with all the data and information that are inside the model.» (Interview with researcher, 13 09 2019)

The idea is that just as BIM currently automates clash detection, a suite of tools could help do a simplified analysis of environmental and energy impacts on models. However, getting from data on environmentally sustainable projects to decisions about those projects entails "technical boundary spanners"[17] who can bridge the differences across communities of practice and the narrative sensemaking[18] to get teams to enact those decisions.

The BIM manager recognized the challenges of expanding the scope for data-driven innovation with BIM. The first challenge is the cost entailed to set up the data environment for analysis in the first place. 'If we want a real 5D, 6D and 7D [integrated cost, facility management and environmental analysis in BIM], we will need to increase the project cost, but we will get a richer project to make all other wonderful Ds.' He continued:

17 Dossick, C.S., Neff, G., Osburn, L., Monson, C., Burpee, H., 2016. Technical boundary spanners and translation: A study of energy modeling for high performance hospitals.

18 Osburn, L., Neff, G., Dossick, C.S., Monson, C., Burpee, H., 2019. Narrative Infrastructure in Decision-making: How teams use stories and sensemaking for strategy. Proceedings of the Engineering Project Organizations Conference, Vail, Colorado, June 2019.

> «Passing to more Ds means more data. You have to think about how to manage it, and you have to care of this data… The challenge is the "data". It demands new roles in the project.» (Interview with BIM manager, 13 09 2019)

The potential for BIM data to be used for analysis to support environmental impact analysis is there, but it requires potentially more time, money, and analysis in order to use it for decision making. Still, our interviews suggested that the data could "drive" these kinds of activities for the building design and construction. The researcher suggested that architects could have a BIM-enabled tool that «gives you some kind of indication on all these different parameters, not only about cost or other things considered from the beginning but also about environmental and sustainability» (Interview with researcher, 13 09 2019).

On some projects, there will be an energy model or energy simulation. This is so efforts can be made to optimize the design for a building's energy efficiency. The energy aspect of sustainability is what this research work has been focused on. So, in the interviews, there is a focus on that, and several information emerged.

Architects' BIM models play a significant role in energy optimization, and people building energy simulation and models rely on information from the architects about the design and potential uses of the building. We asked the mechanical engineer, «Do you use BIM on all your projects?» she replied «No, because on other projects where there is no one working at BIM, it is difficult for us to do our part without an architectural model, so we are dependent on others.» (Interview with MEP engineer, 30 08 2019). We asked to follow on questions to try to understand better the relationship between mechanical engineers doing energy optimization design and the architects. Can she do her job when architects do not share a BIM model? She replied:

> «Unfortunately, no! There are also projects where architects, who usually use BIM, decide that it is not worth using it or [they do] not need it, so we are forced to work on CAD, despite having invested in buying the software license and we are willing to use it. Sometimes it happens that, as in another project on which I'm working, I started to make myself the architectural model because I needed to do a 3D model of some parts to study the interaction and overlap of the pipes.» (Interview with MEP engineer, 30 08 2019)

Some analyses can be done inside the BIM environment. However, many of the energy simulations and sustainable analysis, are still performed outside the BIM environment with different software. However, having a complete BIM model as a starting point allows someone doing energy analysis to have accurate and up-to-date assumptions about the project. There are, however, problems of interoperability between the different software packages. Sometimes, according to the BIM manager, it is challenging to integrate energy models into the workflow on large-scale projects and without the close connection to architectural design, making it even harder to get the results back into consideration for the model and the project (Interview with BIM manager, 13 09 2019). Another challenge is that optimization software tools often rely on different starting assumptions and requirements, according to the researcher we interviewed, who continued:

> «We need the information to be very, very accurate in order to provide accurate results. We need this model to be complete, with all accurate information about the materials, spaces, energy systems ... It was almost impossible to obtain information from the BIM model.» (Interview with researcher, 13 09 2019)

The workaround is to carry out energy simulations outside the BIM environment, taking input data directly from the BIM model. Without currently an easily integrated tool for architectural and mechanical models to do energy simulations with, one of the most considerable difficulties is «the time required to ensure that the BIM models are complete and accurate in order to ensure the quality of all processes. Because in the end, our tool is reliant on these models, so if the model is not correct, the tool will never give good results.» (Interview with researcher, 13 09 2019)

The time to create accurate models, full of all the necessary information, is one of the biggest problems and, in the current difficulties of using BIM, is a key element that discourages users. Neverthless, when Building Information Models are built and shared across communities of practice, they create new opportunities for other kinds of problem solving across the project. As the BIM manager said, «you get gold from the model if you put gold in the model».

5.2 BIM: new process or new technology?

Current building projects are notoriously complex and intensely collaborative due to the many experts that get involved at different times of a project and deploying each of their different tools and standards[19]. In addition to the architects and building engineers, technical specialists, clients, perhaps one or several end-users communities, planning, regulatory authorities, and citizens could be involved.

All groups involved in design processes (architects, engineers, builders, etc.) could be considered as "communities of practice"[20]. Communities of practice are defined by Wenger (1998) as "social configurations" where people engage in practices, negotiate to mean, and create their identities. It cannot be formally identified as an organizational entity or a group of people having the same job or the same title[21]. Instead, communities of practice are identified through participation in the mutual commitment of the people involved[22]: members interact and learn together about a particular domain[23]. Three characteristics of the Communities of practice are defined by Wenger: domain, community, and practice. These groups find themselves having to share work and information with others in a new way. In this way, they develop a shared repository of resources (knowledge, documents, experiences, stories, tools, etc.) useful to address recurring problems: a shared practice[24]. As already mentioned, people from different communities of practice and with different experiences and knowledge were selected for the interviews.

Recent studies investigate if and how BIM could be a new way to achieve collaborative design and construction processes[25]. Taking a socio-technical perspective, it is

19 Møller, N., Bjorn, P., 2016. In Due Time: Decision-Making in Architectural Design of Hospitals. Møller, N.L.H., Bansler, J.P., 2017. Building Information Modeling: The Dream of Perfect Information. https://doi.org/10.18420/ecscw2017-24. Dossick, C.S., Neff, G., 2011. Messy talk and clean technology: communication, problem-solving and collaboration using Building Information Modelling. Engineering Project Organization Journal 1, 83–93. https://doi.org/10.1080/21573727.2011.569929
20 Wenger, E., 1998. Communities of practice: Learning, meaning, and identity, Communities of practice: Learning, meaning, and identity. Cambridge University Press, New York, NY, US. https://doi.org/10.1017/CBO9780511803932
21 Wenger, E., 2011. Communities of practice: A brief introduction.
22 Lee, C.P., 2007. Boundary Negotiating Artifacts: Unbinding the Routine of Boundary Objects and Embracing Chaos in Collaborative Work. Computer Supported Cooperative Work (CSCW) 16, 307–339. https://doi.org/10.1007/s10606-007-9044-5
23 Wenger, E., 2011. *Ibid.*
24 Wenger, E., 2011. *Ibid.* Smith, S.U., Hayes, S., Shea, P., 2017. A Critical Review of the Use of Wenger's Community of Practice (CoP) Theoretical Framework in Online and Blended Learning Research, 2000-2014. Online Learning 21. https://doi.org/10.24059/olj.v21i1.963
25 Dossick, C., Osburn, L., Neff, G., 2019. Innovation through practice. Engineering, Construction and Architectural Management. https://doi.org/10.1108/ECAM-12-2017-0272

clear how focusing on new types of interaction across communities of practice becomes critical new collaborative technologies. If we are to solve the grand challenges such as sustainability, it takes a new approach to the construction design through the support of the new digitized world.

In section 5.1, it is shown how sustainability is poorly supported by BIM and Common Data Environments (CDE) tools and platforms. A further aspect emerges from the data collected through the interviews: depending on the communities of practices to which they belong and the role they hold, experts have a different point of engagement when seeing BIM as being shaped by what Fiore-Gartland and Neff call "data valences"[26]. It is a new way to describe the differences expectations for data across communities of practice. Data values can change in multiple contexts, stakeholders, and interactions[27] between the communities of practice of a construction process. The data is an opportunity for conversation and connection between the communities of practice. They can be challenged at the boundaries of the communities and can offer "voice" and expression for the development of approaches to translate the various values and expectations of people for the use of the data[28].

In BIM-project dependencies and frequent communication flows of a building project continuously change[29]. BIM, a product or intelligent digital representation of data about a facility, a collaborative process, and a system of information exchanges, workflows, and procedures[30], create new relations between different communities of practice. The positive effects of using BIM are available[31], but there are still several difficulties and limits when different communities of practice work together to achieve sustainability.

26 Fiore-Gartland, B., Neff, G., 2015. Communication, Mediation, and the Expectations of Data: Data Valences Across Health and Wellness Communities. International Journal of Communication 9, 19.
27 Fiore-Gartland, B., Neff, G., 2015. *Ibid.*
28 Neff, G., Tanweer, A., Fiore-Gartland, B., Osburn, L.A., 2017. Critique and Contribute: A Practice-Based Framework for Improving Critical Data Studies and Data Science, in: Big Data. https://doi.org/10.1089/big.2016.0050
29 Dossick, C.S., Neff, G., 2010. Organizational Divisions in BIM-Enabled Commercial Construction. https://doi.org/10.1061/(asce)co.1943-7862.0000109
30 buildingSMART Alliance, 2015. "NBIMS-USTM Version 3 | National BIM Standard – United States, National Building Information Modeling Standard". National Institute of Building Sciences, Washington, DC, available on: www.nationalbimstandard.org/buildingSMART-alliance- Releases-NBIMS-US-Version-3
31 Bryde, D., Broquetas, M., Volm, J.M., 2013. The project benefits of Building Information Modelling (BIM). International Journal of Project Management 31, 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001

When the respondents in semi-structured interviews were pushed to consider what BIM could do for sustainability, another relevant fact emerged. Interviewees focused on how BIM's real innovation relies on the transformation of the Common Data Environment and the potential to change how communication, coordination, and collaboration occur on design and building projects. So, they have somehow tried to divert attention, and these aspects, too, may help improve the sustainability of construction.

All the interviewees are focused on the new use of BIM from a technical point of view, describing specific aspects of it and their work with these new kinds of tools. They focus their speeches on the tools for modeling, for example, Revit, Allplan, ArchiCAD, and Navisworks. They focused on the formats of data exchange such as ifc, dwg, e-mail, and phone calls and how they import and export information to collaborators. But more importantly, they identified how new collaborative processes emergent with the new technologies. Take the quote from an interview with an architect, below. A "BIM approach" is a method that changes both the professional and the collaboration process, making it so that "you can hardly do things as before".

> «The other day I had to work on a "no-BIM project" and I realized the waste of time and confusion that you have without a BIM approach: once you discover this method, you can hardly do things as before.» (Interview with architect, 23 07 2019)

This opens up the question of BIM as new technology or new process that it was asked to all respondents. This approach placed much hope onto the potential for how improvements in the building process could lead to more sustainable construction, as illustrated by the quote where an architect explained how she thinks through BIM as a tool for achieving sustainability "in a Greta Thunberg way". Taking this approach allows the architect to conduct a reasoned design and have more control upstream of the entire process, saving energy and conduct a correct and responsible design.

The approach of BIM as a new process with transformative possibilities draws a direct comparison between improving the collaboration process and sustainability outcomes, and offers more opportunities to the designer for outcomes in the construction process, including more efficient construction sites and chances for reducing emissions in the building process. BIM as a new process, in our interviews, entailed respondents describing new features of the design process managed for a BIM perspective. For example, a BIM manager explained:

> «[The] process is more complicated. This is not just purchasing a BIM license and start drawing using it. It's to understand what the clients expect from

> BIM, what are the BIM goals because it is not the same if you want to produce a drawing if you want to coordinate and if you want to extract quantities… So, the question is "what for"?» (Interview with BIM manager, 13 09 2019).

The example that one of the interviewees gave is that we are currently in a situation where one wants a new car but does not know the specifications and therefore does not know how to choose it. Thus, clients and policymakers push for BIM to be used. However, people do not know precisely for what: For modeling the project in 3D, for improving communication across the communities of practice involved in large-scale projects, for coordinating among the subcontractors who build different systems, or for extracting data for to use in other kinds of simulations and analysis.

The technical affordances of BIM for teams on large-scale projects were clear. The teams represented in interviews used strategies to "ensure the correctness and correspondence of the data entered in the model", to organize and to "facilitate communication" and "information exchange between the different teams", and to adopt "to classify everything" using Work Breakdown Structure (WBS), a project management methodology to organize work in more easily manageable elements.

Then, one of the most important technical affordances of BIM is the capacity to automate clash detection. When different building systems are put into the same BIM model, the software can show where systems interfere or clash with one another, say when a plumbing system and electrical conduit collide. For coordination of the mechanical systems of a building, the use of BIM has revolutionized large-scale construction. One BIM manager said that given the challenges and costs of implementing BIM and the efforts to create a Common Data Environment, "It would be worth using BIM even just for three-dimensional coordination to improve the communication". This communication is crucial because it helps to reduce the time spent on the installation of systems, reduces errors and waste, and automates some of the work of coordinating work. Again, the BIM manager:

> In my «opinion, 3D coordination is amazing. We have more than one million clashes in our airport project if we have not been spending time on clash detection, clash meetings, and clash resolution ... Just a small portion of that can be a nightmare for the contractors [on site]. This is one of the main advantages [of BIM].» (Interview with BIM manager, 13 09 2019).

Finally, from the analysis of the data obtained from the interviews, it can be said that BIM is both a new process and a new technology. BIM, as technical innovation, helps to create new opportunities for improving construction. BIM as a process innovation brings teams together for collaboration in unprecedented ways, including tackling sustainability, one of society's biggest challenges.

5.3 The Proposed Methodology

The research presented focuses on investigating and re-interpreting the transformations in our sector, paying particular attention to sustainability aspects, in order to understand how these changes can contribute to generating new processes and behaviours in design. The study of the reference literature and the current situation, the discussion with experts and the implementations realized using the latest generation software available, have led to the definition of a replicable procedure for the optimization of the design and regenerative process of construction.

Based on the whole process, there is the aim to include sustainability from the very beginning of the design concept. References, collected data on the actual situation and the future scenario that is outlined before us, make us understand the urgency of not leaving this aspect out at a later stage. "Sustainability comes later," said one of the interviewees, but sustainability should come sooner. Instead, it should be the first step. In the proposed scheme, the first step is the definition of the project objectives for the achievement of sustainable construction.

The study from the fourth industrial revolution has allowed us to identify the technological innovation that can contribute to transforming the design process profoundly. Building Information Modeling has been chosen as a digital tool to develop the proposed methodology. The BIM, thanks to its peculiarities described and analysed previously, can reduce the fragmentation of communications between experts and collect all the information generated by different disciplines. These aspects can be the keystone to be exploited to support designers to make design choices from the outset with a greater awareness of the impact on the final result in terms of sustainability.

One of the topics that is most frequently dealt with sustainability is energy. So, building performance analysis could be developed in order to asses and evaluate various aspects as solar and thermal energy, ventilation, daylighting, building massing, site orientation as well as the optimization of a building's HVAC systems. Focusing on the global challenges, this kind of simulation is becoming increasingly important in the design process to optimize future energy consumption and to en-

32 Allouhi, A., El Fouih, Y., Kousksou, T., Jamil, A., Zeraouli, Y., Mourad, Y., 2015. Energy consumption and efficiency in buildings: current status and future trends. Foucquier, A., Robert, S., Suard, F., Stéphan, L., Jay, A., 2013. State of the art in building modelling and energy performances prediction: A review. Renewable and Sustainable Energy Reviews 23, 272–288. https://doi.org/10.1016/j.rser.2013.03.004. Shabani, A., Zavalani, O., 2017. Predicting Building Energy Consumption using Engineering and Data Driven Approaches: A Review. European Journal of Engineering Research and Science 2, 44–49. https://doi.org/10.24018/ejers.2017.2.5.352

sure a good result of the project[32]. Optimization means finding the best values of a function with the highest achievable performances under the given constraints, implied or expressed, by maximizing desired factors and minimizing the undesired ones[33]. It consists of finding the most suitable solutions among a wide range of possible options. As shown in chapter 4, optimization methods have been applied in different fields; of course, also in the construction realm. In many disciplines of architecture and construction, it is used to optimize different criteria, including those related to energy and environmental sustainability aspects.

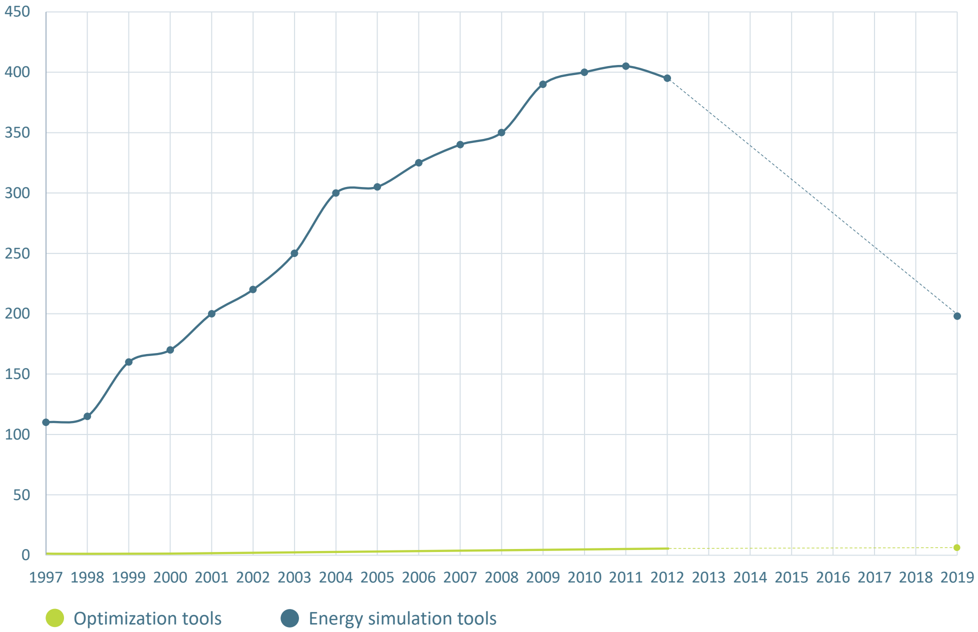


Figure 88 Tool for energy simulation and optimization developed in the last twenty years.

33 Attia, S.G., Hamdy, M., Carlucci, S., Pagliano, L., Bucking, S., Hasan, A., 2015. Building performance optimization of net zero-energy buildings. Modeling, design, and optimization of net-zero energy buildings 175–202. https://doi.org/10.1002/9783433604625.ch05

Several tools for the energy simulation of buildings have been developed over the past decades to assess performance and energy consumption, but only a few dozen have been developed for optimization (Figure 88). 198 software tools are list on the U.S. Department of Energy website, and most of these are set up to simulate the performance of, for example, the building plant systems. Despite this variety of existing tools and many agreeing on the importance of doing something about climate change, not all architectural teams use them or if they are used, mostly as tools for post-design evaluation[34]. Several studies have shown the potential to support the identification of optimal design decisions and that approximately 20% of design decisions made in the early design stage account for 80% of the total impact on the final building energy performance[35]. In these early stages, the architects can make choices oriented towards sustainability, also relying on the advice of sub-communities of practice specialized, but as can be seen from prior research, the task is left to the engineers to make assessments and energy optimizations at a later stage. It follows that the tools and standards used by architects are not the same as the tools and standards used by the MEP engineers, given the different purposes and timing of their work.

Architects act from the very beginning by designing and defining all the details of the construction: it is the creative phase of the project, and the number of details and data increases as the process progresses. MEP engineers are usually involved later when many decisions about the building have already been made (position, orientation, shape, etc.). They are called upon to carry out detailed studies and simulations and have a lot of data to do so, but in return, they are left with minimal freedom for changes to the design. So, it is clear that how they will construct and share information through a BIM-model is complicated.

Two decades ago, the main reason that architectural firms would not use energy optimization tools in the design process were: the lack of pressure/appreciation from the client, high software cost, insufficient staff training/skills, and not user-friendly interfaces that would extend the, already limited, design time[36].

34 Tian, Z.C., Chen, W.Q., Tang, P., Wang, J.G., Shi, X., 2015. Building Energy Optimization Tools and Their Applicability in Architectural Conceptual Design Stage. Energy Procedia, 6th International Building Physics Conference, IBPC 2015 78, 2572–2577. https://doi.org/10.1016/j.egypro.2015.11.288 . Weytjens, L., Verbeeck, G., 2010. Towards "architect-friendly" energy evaluation tools. Presented at the Spring Simulation Multiconference 2010, SpringSim'10, p. 179. https://doi.org/10.1145/1878537.1878724

35 Tian et al. 2015. *Ibid.*

36 Wong, N.H., Lam, K., Feriadi, H., 2000. The use of performance-based simulation tools for building design and evaluation - A Singapore perspective. Building and Environment - BLDG ENVIRON 35, 709–736. https://doi.org/10.1016/S0360-1323(99)00059-1

Today, this situation has already changed, and the tools are widely used in both architecture and engineering firms[37]. However, the assessment of energy optimization, as part of what we consider the sustainability of a building, is still a complicated procedure, which usually requires a significant amount of effort, time, and special skills. Furthermore, to reduce the effort of coordination across the multiple actors involved, energy optimization is generally conducted after the decision on major building elements, or in 2-3 alternative solutions[38].

In the traditional process, to analyse the energy performance with a specific tool, the geometric building information are extracted from the architectural drawings and documents. To use these no-BIM tools, a detailed model of the building is necessary, with all the information related to the characteristics of the envelope, systems, climatic data, etc. After that, the building energy analyst uses this information to define and create the thermal model of the building with the energy simulation tool. The result depends on the knowledge, skill, and experience of the energy analyst: various building energy analysts will, therefore, generate differing thermal views[39]. Several tools for energy simulation are available. The most used software in the world for energy simulation are Energy+[40] and TRNSYS[41]. Moreover, if these simulations are carried out, not only to assess energy performance but also to optimize the design solution, an additional optimization tool is needed.

The diagram in Figure 89 shows the essential steps of a simulation and optimization process of a building in a traditional process. It starts from a 3D model from that all the available information are extracted (1); then all the specific information related to the simulation that is being done are entered (2); all these data are input for the optimization tool (3); finally, the result related to the set objectives is obtained (4).

37 Monson, C., Dossick, C.S., Neff, G., Osburn, L., Burpee, H., 2016. Finding connections between design processes and institutional forces on integrated aec teams for high performance energy design 15. Bambardekar, S., Poerschke, U., 2009. The architect as performer of energy simulation in the early design stage 8.

38 Touloupaki, E., Theodosiou, T., 2017. Optimization of Building form to Minimize Energy Consumption through Parametric Modelling. Procedia Environmental Sciences 38, 509–514. https://doi.org/10.1016/j.proenv.2017.03.114

39 Bazjanac, V., 2007. Impact of the U.S. National Building Information Model Standard (NBIMS) on Building Energy Performance Simulation.

40 EnergyPlus™ is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings. EnergyPlus is free, open-source, and cross-platform—it runs on the Windows, Mac OS X, and Linux operating systems. Its development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO).

41 TRNSYS is a flexible graphically based software environment used to simulate the behaviour of transient systems. TRNSYS is a commercial software package developed at the University of Wisconsin.

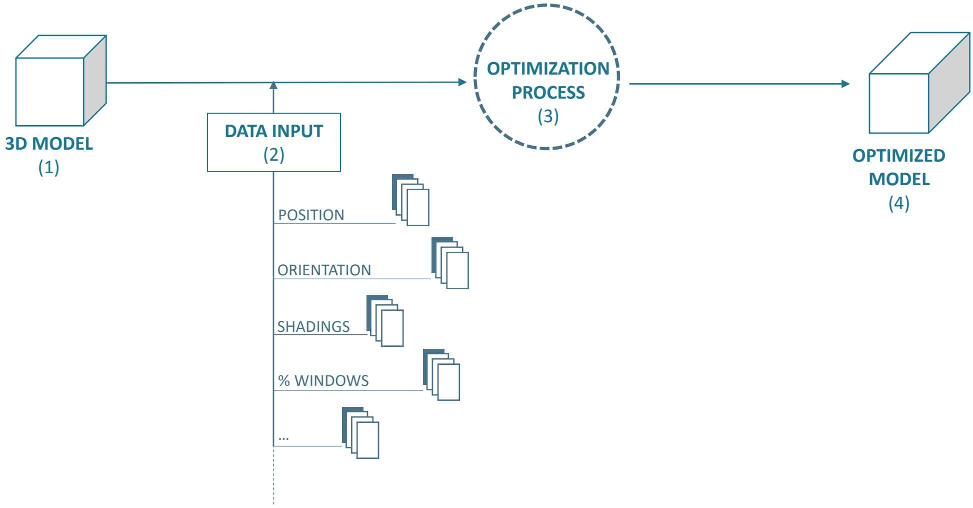


Figure 89 Outline of a traditional optimization process.

The BIM model is a huge repository of all the data of the entire life cycle of the building. A BIM model does not only include geometric information. It is a complete digital representation of all physical and functional characteristics of the building (Figure 90). Perform simulations and optimization processes in the BIM environment allow us to benefit from the peculiarities of it as an independent and multi-disciplinary data repository.

Using Building Information Modeling for the optimization of energy consumption, the process described earlier in the traditional way, can speed up. The scheme shows before is now simplified. The second step, which involved adding the missing data to complete the model for the performance simulate, can be deleted due to all the available information are included in the BIM model.

Figure 91 shows the process developed using BIM. It starts from a BIM model that includes information (1); the information needed for the simulation are select and then entered in the optimization tool (2); finally, the result related to the set objectives is obtained (3).

Based on these considerations and the combination of the three key arguments - sustainability, digitization, and optimization - the methodology proposed in Figure 92 has been defined. The scheme is composed of several steps that will be deepened in the next pages, and then some developed application examples will be described.

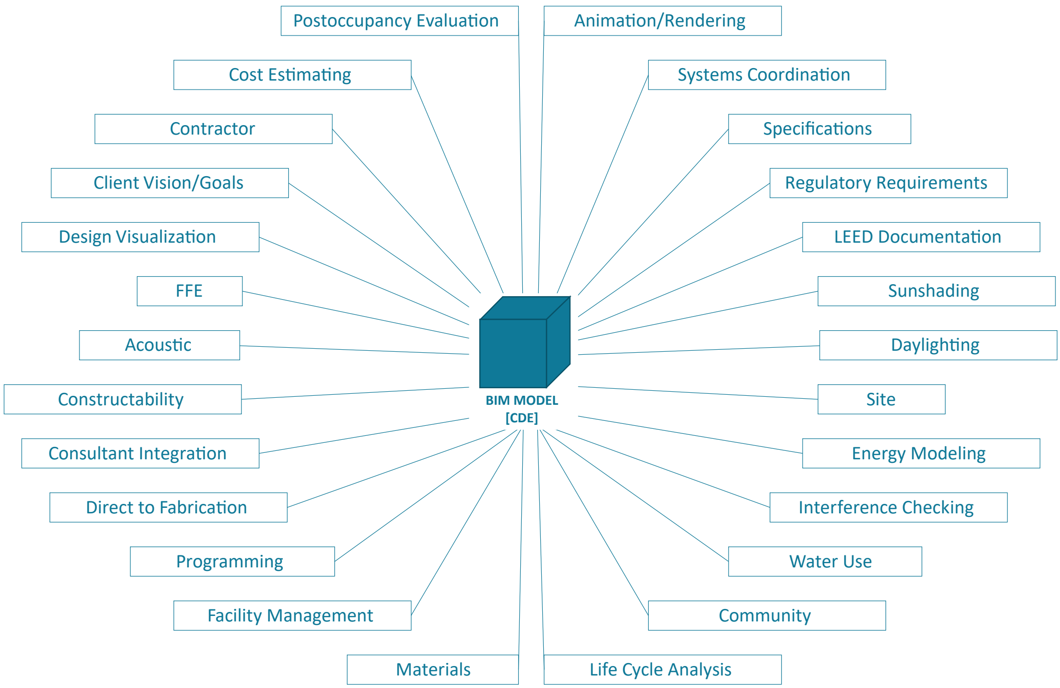


Figure 90 Schema of all the data included in the Common Data Environment of a BIM model.

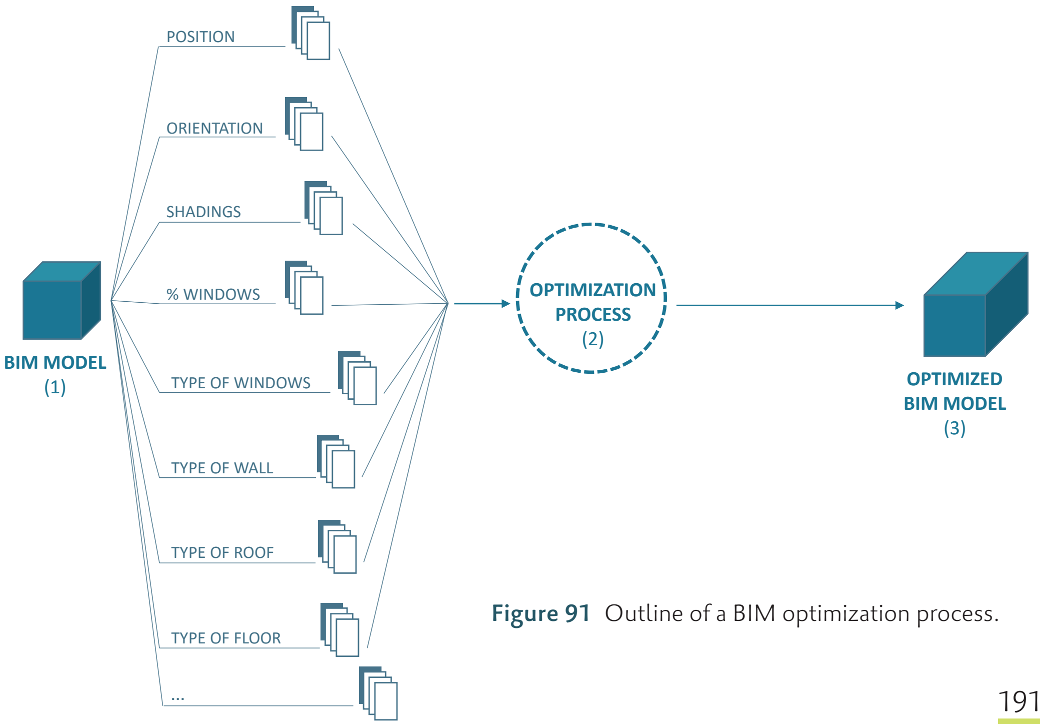


Figure 91 Outline of a BIM optimization process.

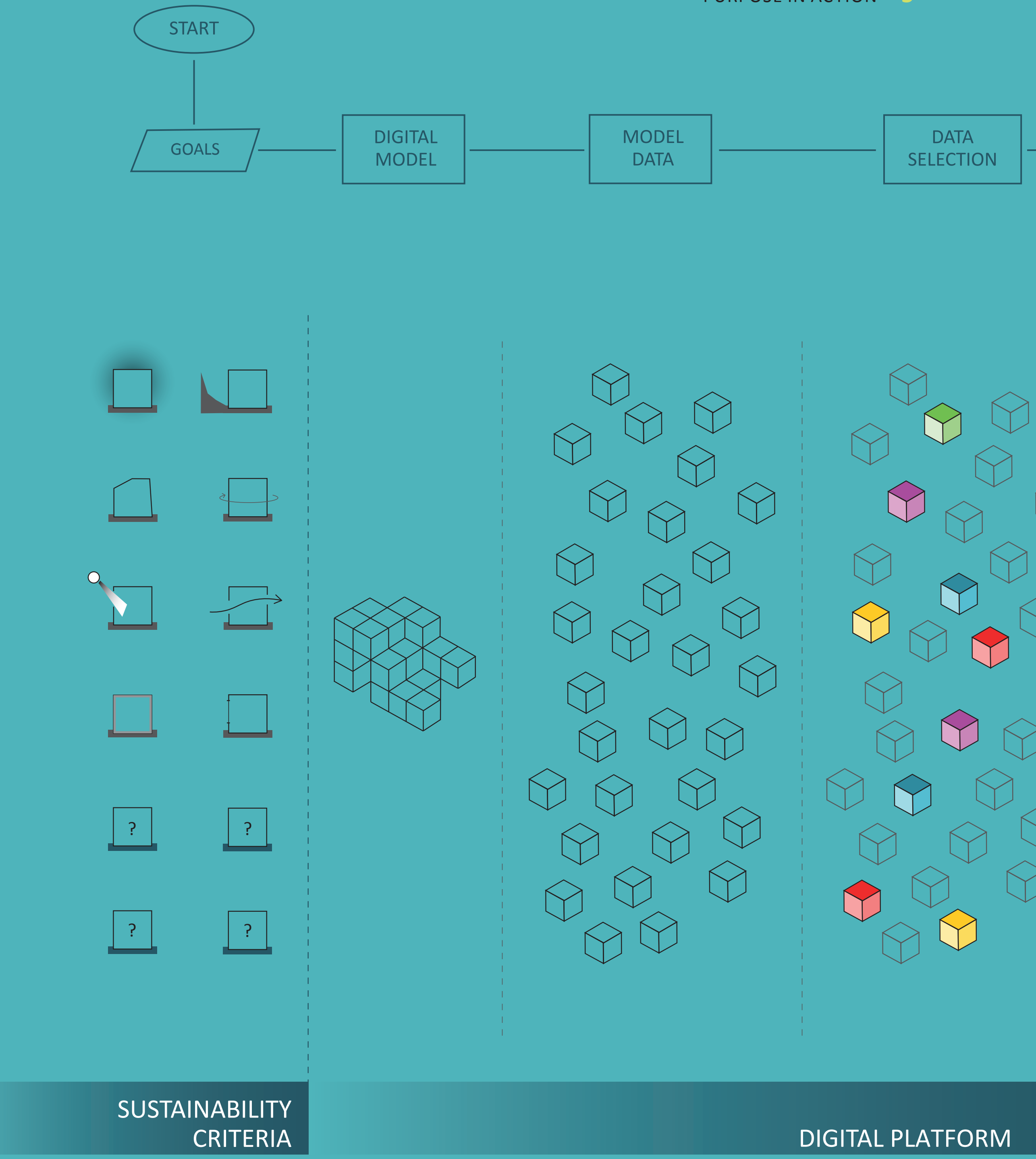
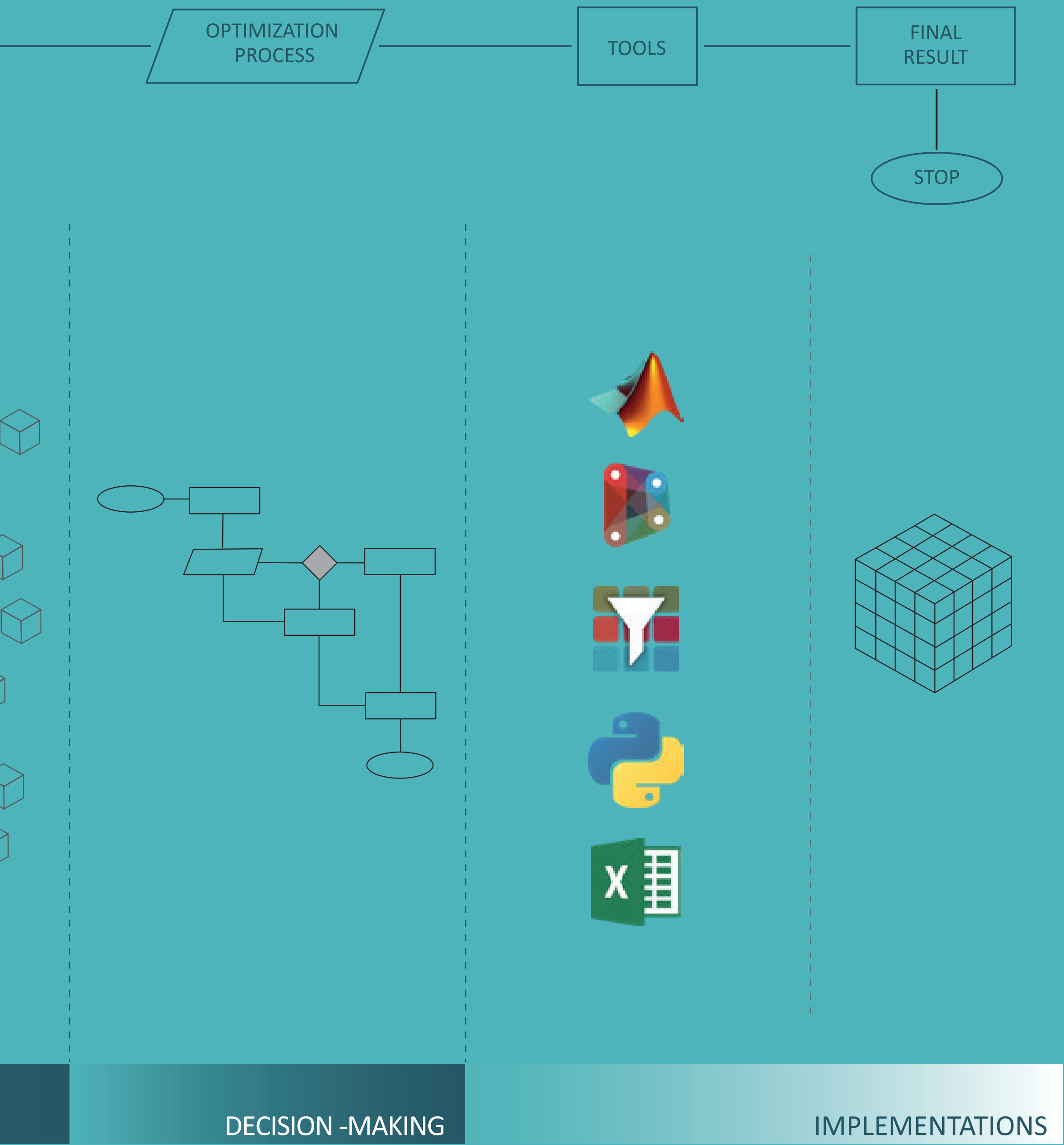
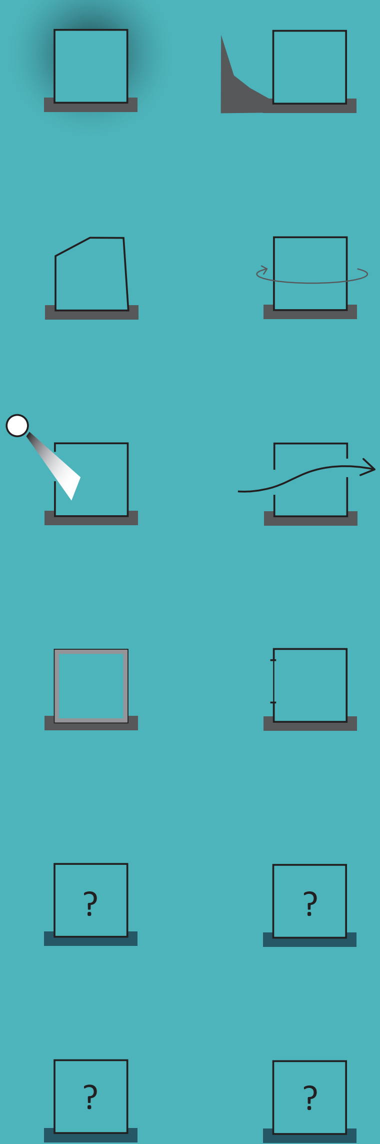


Figure 92 Schema of the proposed methodology:


OPTIMIZATION PROCESS
TOOLS
FINAL RESULT
STOP
DECISION -MAKING
IMPLEMENTATIONS



GOALS

The first step to be taken is to establish the goals that must be met based on the aims of the project. Besides, it is necessary to define whether there are constraints that restrict the scope of identifiable feasible solutions.

The multiple goals of an architectural project can be enclosed in the three pillars of sustainable development: environmental, social, and economic. These can include objectives such as energy, economic, comfort, environmental, social, urban planning, etc. Within these macro-categories, specific objectives can be identified. For example, considering the general goal to reduce the final energy consumption of the building, this can be translated into the specific objectives concerning (Figure 93):

- Position and orientation;
- Opaque envelope's characteristics;
- Transparent envelope's characteristics;
- Passive solar systems and solar protection;
- HVAC installation;
- Daylighting;
- Natural ventilation;
- Indoor climatic conditions;
- PV panels' position;
- ...

The implemented examples, shown in the following paragraph, have been developed by selecting some of the objectives listed above related to the building's energy consumption field. Despite the procedures and logic with which they have been developed, they can be extended and adapted to other project objectives.

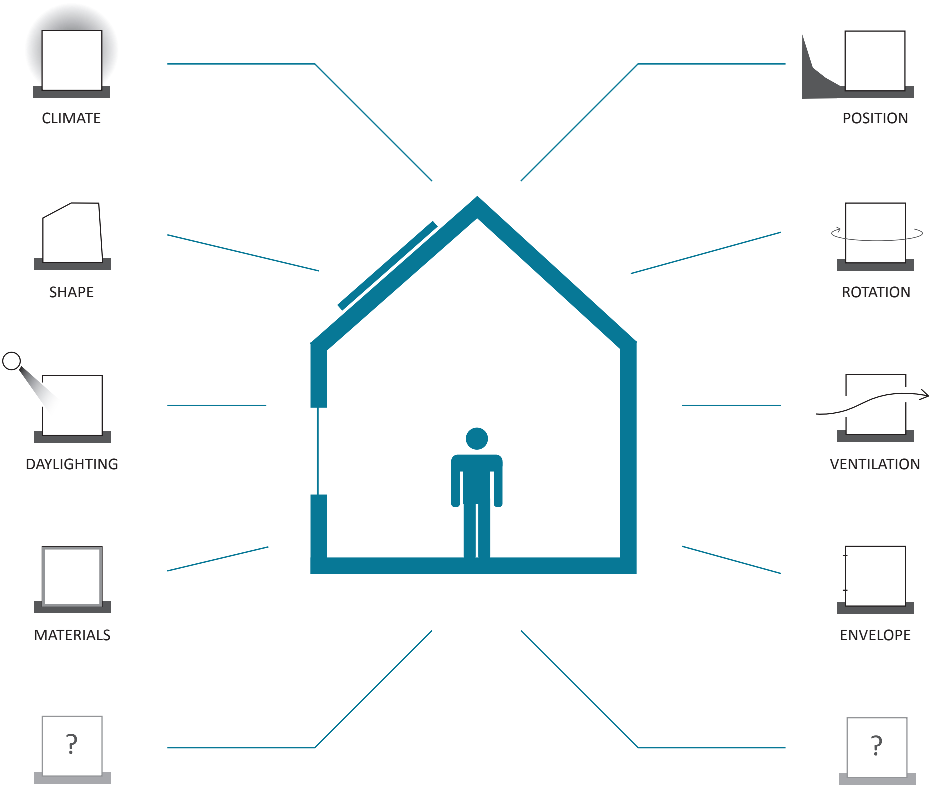
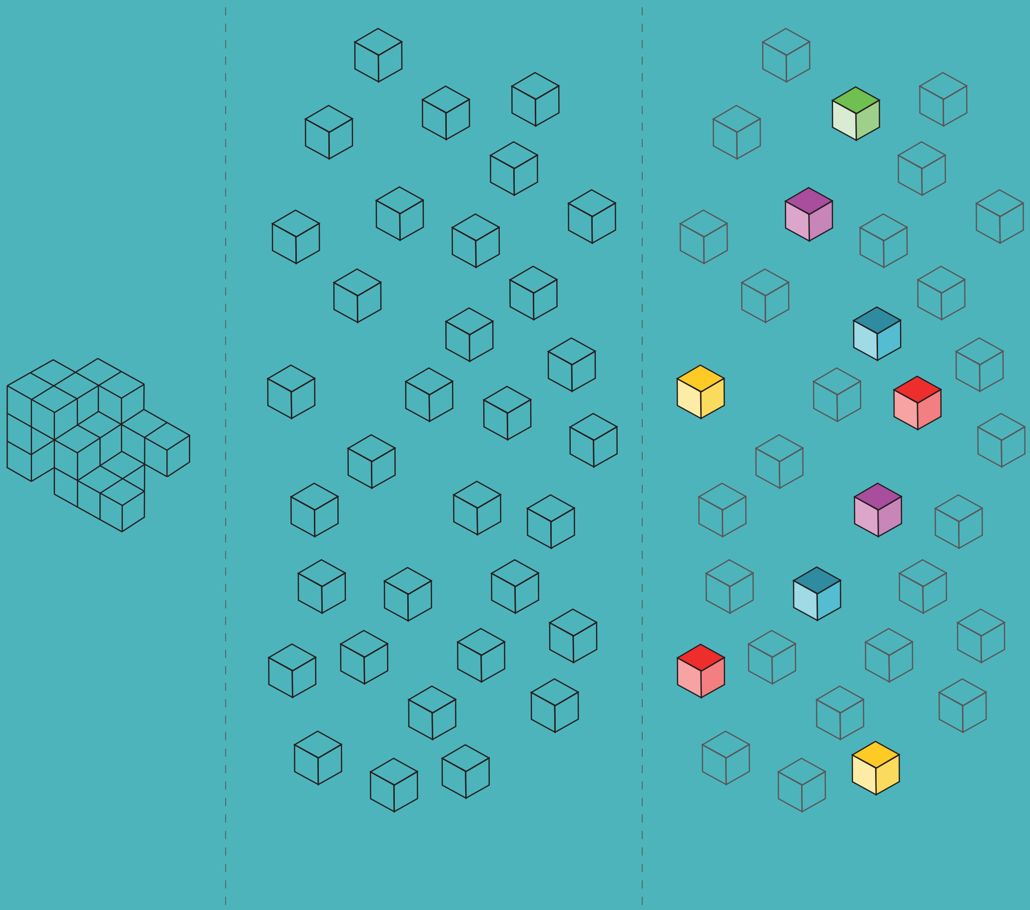


Figure 93 Example of optimization goals for sustainable design.

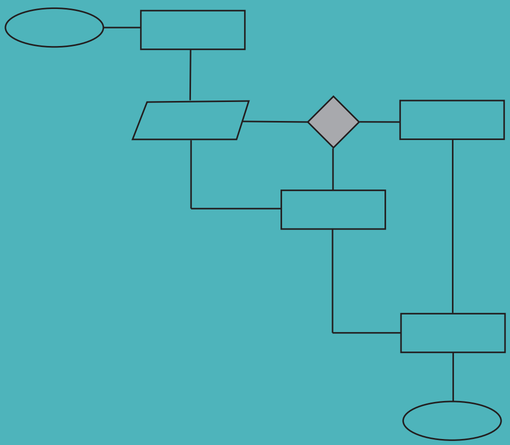


DIGITAL MODEL AND DATA SELECTION

The next steps are related to the development of the digital model and the selection of data useful for the optimization process. The digital platform chosen is Building Information Modeling and, more specifically, Autodesk Revit for the development of BIM models used in the implementations presented below. The BIM model is the key to the methodology. Thanks to its features already described and analyzed above, it avoids the need to collect and implement missing information for the development of the entire process. Everything that is developed in the design process is contained within the BIM model.

Once the goals and constraints have been set, the next step concerning the digital model of the building in order to explore and extract the input data necessary to develop the optimization process. For the example on the optimization of energy aspects, the following design variables could be selected:

- weather data;
- building orientation;
- building geometry;
- thermophysical properties and thickness of the envelope's materials (walls, roof, floor, windows etc.)
- type of building envelope's materials;
- window to wall ratio;
- window type and dimensions;
- amount of glazing;
- ventilation rate;
- design and operation parameters of HVAC systems;
- building usage, including functional use;
- internal loads and schedules for lighting occupants, and equipment,
- heating, ventilating, and air-conditioning (HVAC) system type and operating characteristics;
- ...



OPTIMIZATION PROCESS

The next phase of the methodology is the formulation of the optimization process. There are some elements common to all optimization problems which consist of:

- A set of independent variables or design parameters;
- A set of constraints that bound the respective;
- domains of the independent and dependent variables;
- One or more objectives to be optimized.

At this stage, it is already verified that we have all these elements necessary to build the optimization process. Then the methodology proceeds with the identification of the resolution technique to be used among all those belonging to the decision-making methods. There are many techniques applicable to complex optimization problems, but not all of them are adequate and applicable in the field of construction and for the type of information available. The choice of the most suitable one is therefore made based on the following characteristics of the problem:

- number of decision-makers;
- number of goals;
- information from the decision-maker on possible solutions;
- information from the decision-maker on attributes.

Specifically, for the development of the applications presented below, the optimization processes were generated in BIM using Autodesk Revit to generate the digital model and then Dynamo, for the visual programming. Dynamo is available in the standalone version and the version directly integrated inside Autodesk Revit.

TOOLS

In the previous phases, the objectives were identified, the digital model was developed, and the data and methods were chosen. Thanks to all this information, it is possible now using specific software to develop the optimization process and solve the problem.

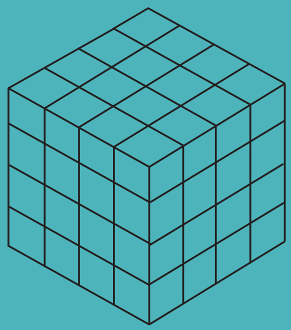
There are some existing optimization tools specifically developed for that and including the resolution techniques seen in Chapter 4, but thanks to visual programming tools, as Dynamo or the other one mostly used Grasshopper, it is also possible to write new ones.

In the implementations presented below, both existing optimization tools and tools for writing new processes were used. The tools used are:

- Autodesk Dynamo
  It is an open-source graphical programming interface that allows customizing the building information workflow within Autodesk Revit. Inside Dynamo the designer can define rules/concepts linking the optimization process to the BIM digital model in order to generated design solutions. In Dynamo workspace, the user can use nodes and wires to specify the logical flow. Each node operates and has receptors for wires that supply the input data to the node as well as the results of the node's action. Wires connect between Nodes to create relationships, and they can be thought of as electrical wires that carry pulses of data from one object to the next.
- Python
  It is a high-level object-oriented programming language suitable to develop distributed applications, scripting, nu-

merical computing, and system testing. Within Dynamo, the Python plugin has been used to write some new parts of the optimization processes.

- Refinery
  It is a generative design tool developed by Autodesk for the architecture, engineering, and construction industry. It gives users the power to quickly explore, evaluate, and optimize their Revit and Dynamo designs using genetic algorithms. Refinery is still a beta project.
- Microsoft Excel
  It is a spreadsheet developed by Microsoft for Windows, macOS, Android, and iOS. It features calculation, graphing tools, pivot tables, and a macro programming language called Visual Basic for Applications. Using Dynamo, it is possible to export the data of the model and processes developed into Excel. This process has been useful to be able to rework the data and to import them into other software.
- Matlab
  It is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages. MATLAB has been used to write new optimization processes using data extracted from Revit with Dynamo and Excel.



FINAL RESULT

The result of the optimization process, after several iterations and the elimination of unfit solutions, is an optimal solution or a pool of optimized design alternatives that meet the objective functions set. From this, the designer can obtain indications on the design solutions that allow him to make his choices with greater awareness and face highly complex problems such as the evaluation of the sustainable aspects of construction from the beginning.

5.4 Implementations

In this paragraph, six examples of possible uses of the methodology developed are presented. The applications developed are:

- **[1]** Properties' optimization of the transparent envelope
- **[2]** Properties' optimization of the opaque envelope
- **[3]** Properties' optimization of the entire envelope
- **[4]** Optimization of façade's geometry
- **[5]** Volume and solar radiation optimization
- **[6]** Selection of the best solution using attributes

The examples have been diversified in order to achieve different goals related to sustainable design, to use different tools and calculation methods for the resolution of the optimization process. The case studies shown have been realized on prototypes to focus the attention on the whole process, rather than on the digital model development. Despite this, as will be described below, all applications are adaptable and replicable on projects of greater complexity.

[1] Properties' optimization of the transparent envelope

Goal The objective of the script [1] is to optimize the thermal performance of the transparent elements present, in terms of thermal resistance [m^2K/W], keeping the geometrical characteristics fixed. Specifically, we want to exploit the potential of BIM to be a database of digital objects. The example aims to compare the elements inserted in the digital model with those present in the database and to make replacements if objects with "better" thermal performance are identified.

Digital Model The digital model developed in Autodesk Revit is a building consisting of a single compartment with a size of 10 m by 10 m and 3 m height. The starting building envelope consists of the following elements:

- The first floor is a brick slab;
- vertical external brick walls with cavity insulation;
- single-glazed PVC windows and doors;
- flat roof made of the brick slab and extrados insulation.

No entrance doors and internal partitions have been inserted in the model; a window frame has been inserted for each side, and all four elements have different geometric characteristics.

The following images show the plan of the building with the geometrical indications of the doors and windows and the construction (Figure 94) and a three-dimensional view of the exploded prototype (Figure 95).

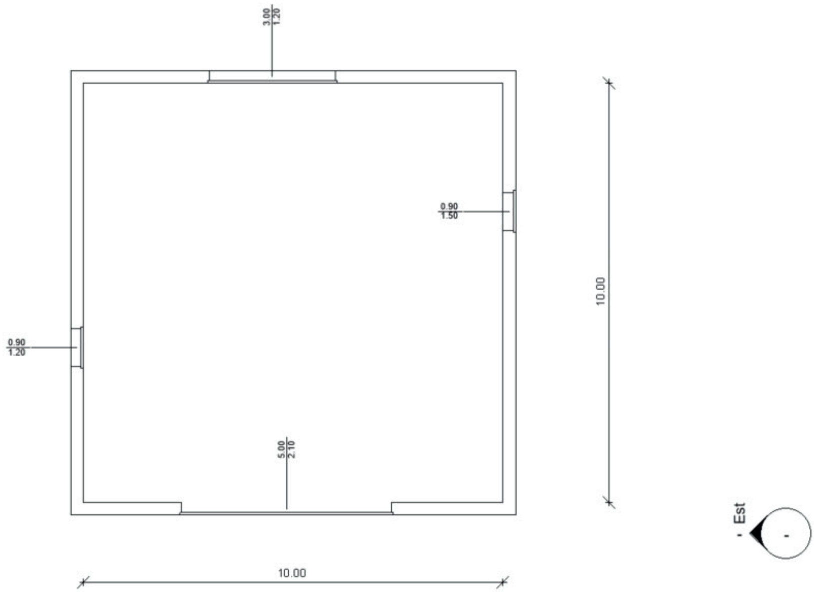


Figure 94 Plan of the digital model developed in Autodesk Revit.

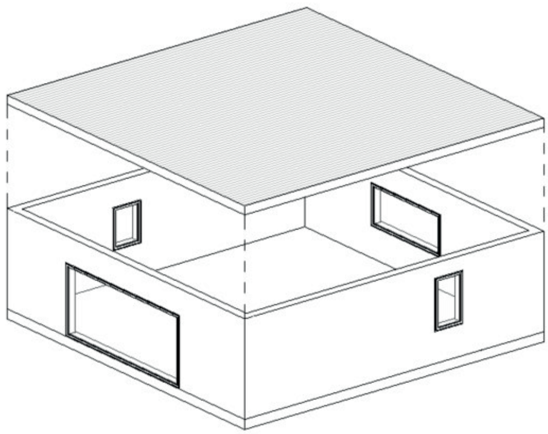


Figure 95 3D view of the exploded view of the digital model developed in Autodesk Revit.

Data selection The optimization process was developed by extracting information on the thermal performance of two types of elements contained in the BIM digital model:

- the data associated with each "Window" instance inserted in the 3D model;
- the data associated with all the "Window" families contained in the database contained in the Revit project file.

Each BIM authoring application includes a set of object classes is called a BIM object library or only a library or a family. Object classes are the information structures for defining object instances. Architectural BIM design tools have object classes for Walls, Doors, Slabs, Windows, Roofs, etc. The object class defines how instances of a class are structured, which type of information they include and how they are edited. The user can expand the BIM library by importing new objects that can be provided by manufacturers, found in online databases or independently produced.

The BIM template is generated by first selecting the object family and then inserting the objects in the template that are named "instances". For example, in the model created for this application, the "PVC window with single glass" family has been used and the instances are the four windows inserted in the model.

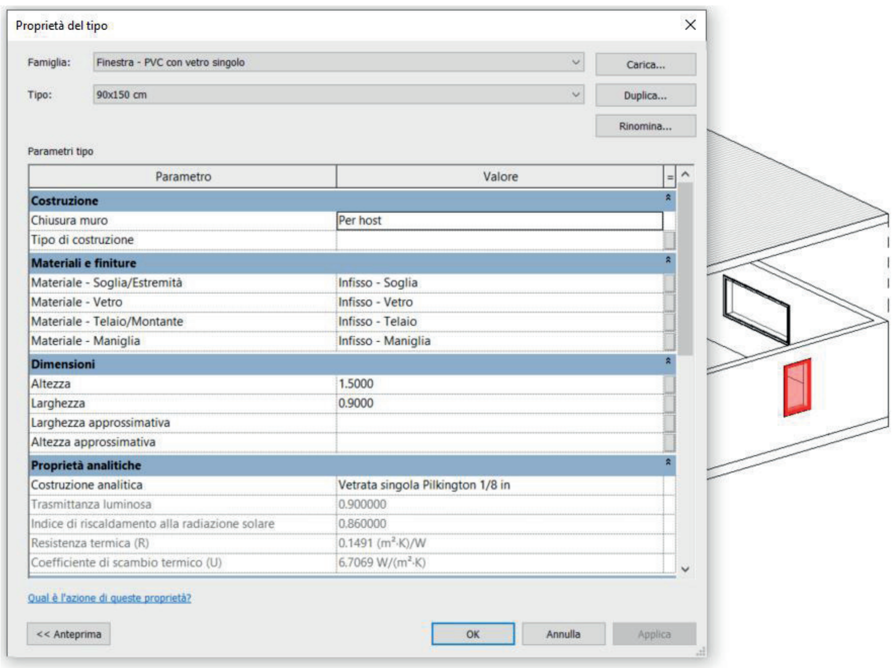


Figure 96 Properties tab of a window in Autodesk Revit.

The families and instances contain the properties and attributes of the object, such as its dimensions, materials used, physical properties, etc. The information can be viewed and edited in the BIM authoring program by accessing the properties tab (Figure 96).

The developed script then uses the data on thermal properties contained in the four drawn windows and all the other "Windows" families present in the BIM model database.

Optimization process The optimization process has been structured, as shown in Figure 97. After defining the target, the BIM model is drawn and then is linked to the visual programming program. The script developed in Dynamo allows extracting the data of the families and instances of the BIM model. We then proceed with the comparison of the transmittance data extracted from each of the four instances drawn with those detected in the database. If values with better performance are found in the database, the script replaces the drawn instance element with the "optimal" one in terms of thermal resistance but keeping the geometrical dimensions unchanged.

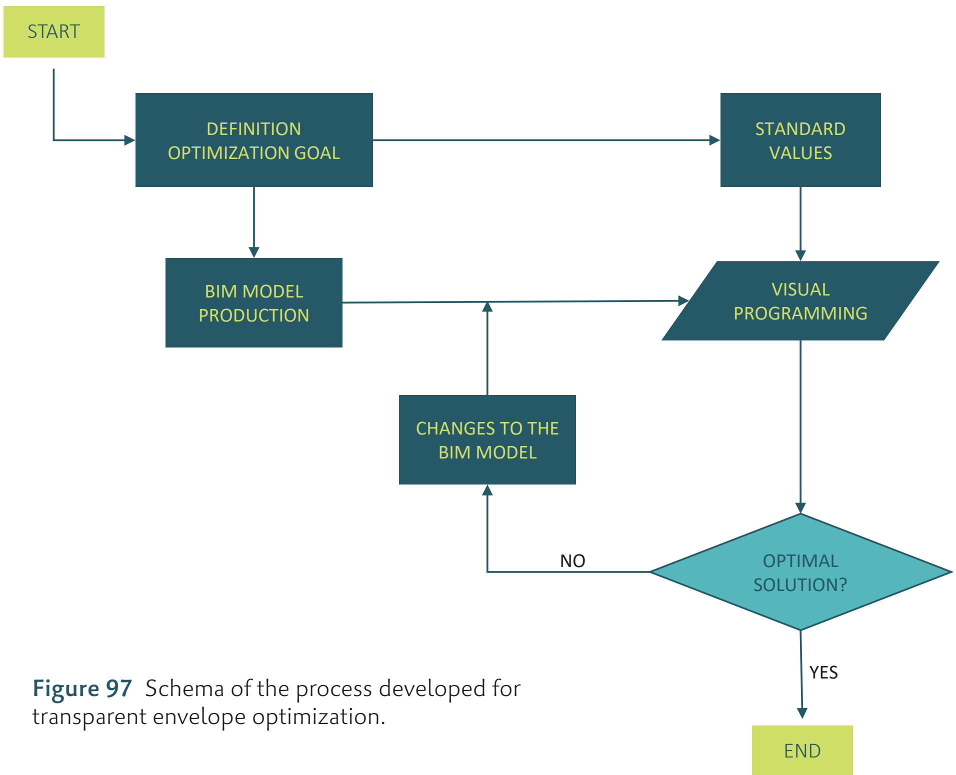


Figure 97 Schema of the process developed for transparent envelope optimization.

Tools The workflow is developed in Dynamo, a visual programming workspace, by connecting Nodes with Wires to specify the logical flow.

The workflow has four main sections of nodes, shown with different colours in Figure 98:

- an initial part allows that links the script to the BIM model and selects a specific type of family, like "window" in this example (blue);
- a part to analyse the model instances and extract the data (green);
- a part to analyse the database and find a better solution (orange);
- a final part allows us to compare the different values and replace the elements if necessary (pink).

See the Appendix for an extended schema of the workflow.

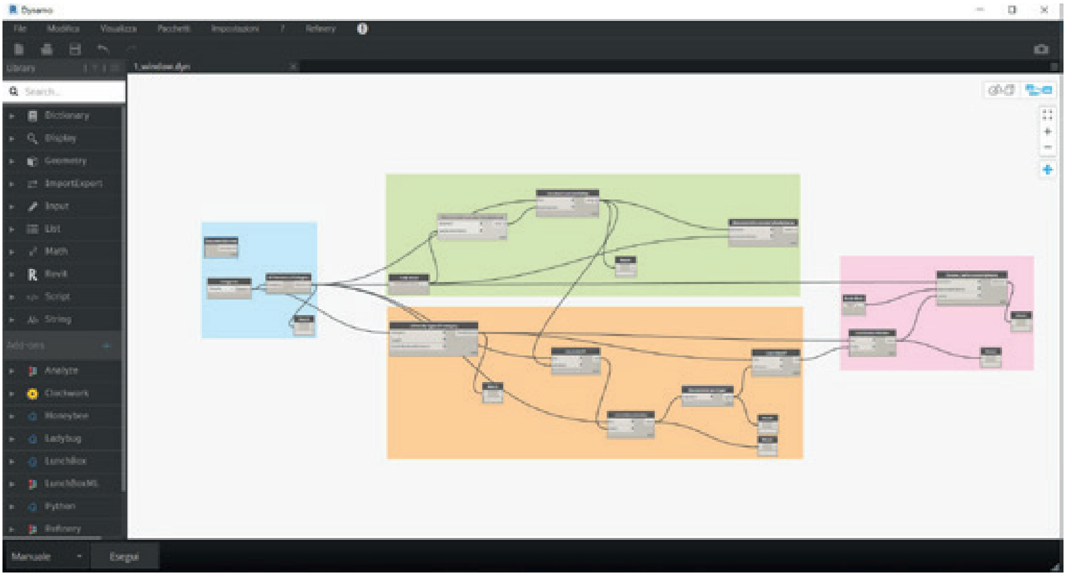


Figure 98 The Dynamo workflow developed. The different sections of the workflow are visible: BIM model (blue); instance analysis (green); database analysis (orange); comparison and substitution (pink).

Final result The final result of the process developed is the digital model optimized concerning the chosen property of the transparent elements, i.e. the thermal resistance. Apparently, from the graphic point of view, there are no changes, but by exploring the elements and properties, the changes made by the process to the glazed elements of the model can be found.

The example described was made on a case with a limited number of objects and selecting a specific parameter. However, the process can be extended to more complicated models both for the number of instances in the model and for the number of families in the database, and will only result in longer waiting time for the calculation. In addition, the thermal resistance parameter can be modified with any other parameter contained in the object family property.

[2] Properties' optimization of the opaque envelope

Goal The objective set for the script [2] is to optimize the thermal performance of the opaque elements present in the model while keeping the geometric characteristics of the building fixed. Specifically, it was chosen to minimize the thermal transmittance value of the vertical opaque elements and to fix a maximum threshold value. The constraint imposed is that of not exceeding the transmittance limit in force in Italy established by Ministerial Decree 26 June 2015. The reference value taken is that corresponding to the external opaque vertical elements of a new building located in climatic zone D: 0.34 W/m^2K.

Digital Model The digital model developed in Autodesk Revit is the same as the previous example. It is a building consisting of a single room that is 10 m by 10 m in size and 3 m high. The starting building envelope consists of the following elements:

- first brick floor;
- vertical external brick walls with cavity insulation;
- single-glazed PVC windows and doors;
- flat brick roof with extrados insulation.

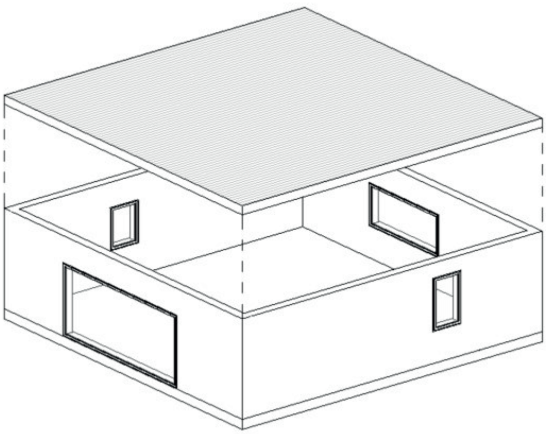


Figure 99 3D view of the exploded view of the digital model developed in Autodesk Revit.

No entrance doors and internal partitions have been inserted in the model; a window frame has been inserted for each side, and all four elements have different geometric characteristics.

The following images show a 3D view of the exploded prototype (Figure 99) and the layers of the external wall (Figure 100).

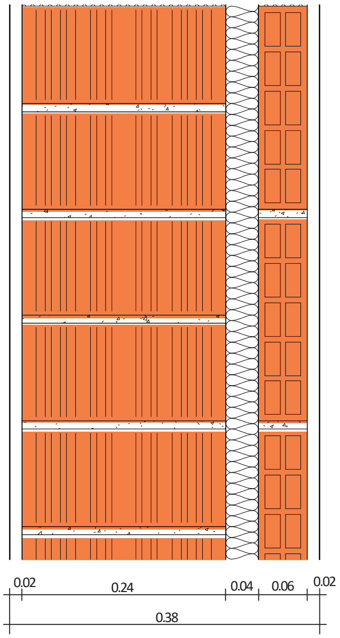


Figure 100 Detail of the vertical wall stratigraphy used in the digital model developed in Autodesk Revit.

Data selection The optimization process was developed by extracting information on the thermal performance of the vertical walls used in the BIM model. All opaque elements belong to the system families divided into "walls", "floors", and "roofs". As in the previous example, the families and instances contain the properties and attributes of the object. However, from the properties tab, the stratigraphy of the elements can be defined and also modified. Figure 101 shows the sheet of the brick masonry with cavity insulation used in the model in which the changes can be made. Specifically, layers can be add or delete and their function, material, and thickness can be modified.

The developed script uses the information on the thermal properties of the drawn instances and the detailed information on the stratigraphy of the single masonry present in the BIM model.

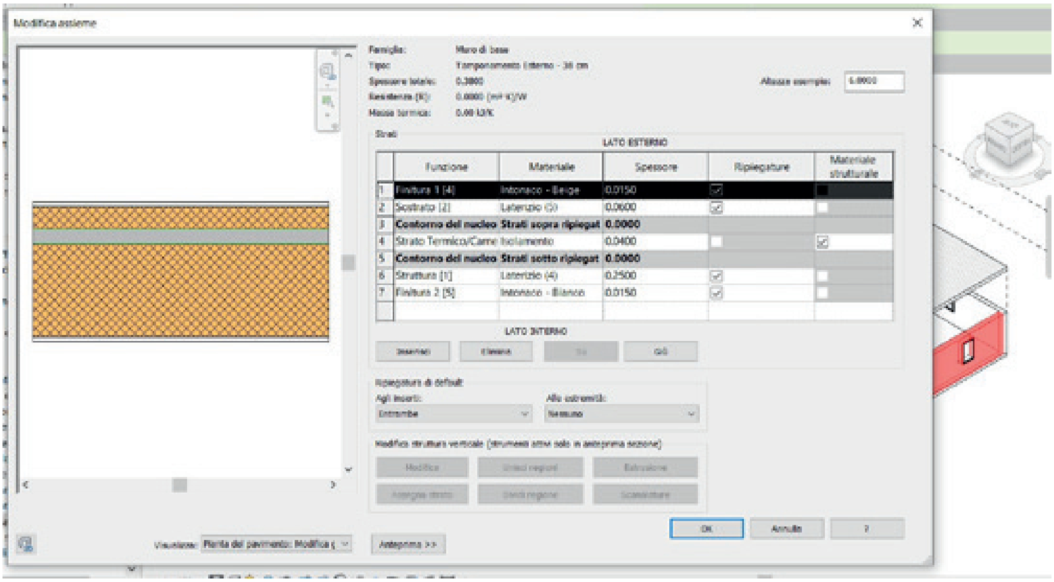


Figure 101 Autodesk Revit's opaque element layering sheet.

Optimization process The optimization process has been structured, as shown in Figure 102. After defining the target, we move on to creating the BIM model, which is then linked to the visual programming program. The script developed in Dynamo allows to extracting the transmittance data and the details of the layers of each instance inserted in the BIM model.

The script allows comparison between the transmittance data of the individual objects drawn and the reference value from the standards. If the verification is not satisfied, then the model is modified. Specifically, the stratigraphy of the instance is analysed, and if there is an element with the function of insulation, the thickness is increased of 0.01 m. This process is repeated until the verification of all instances of the model is satisfied.

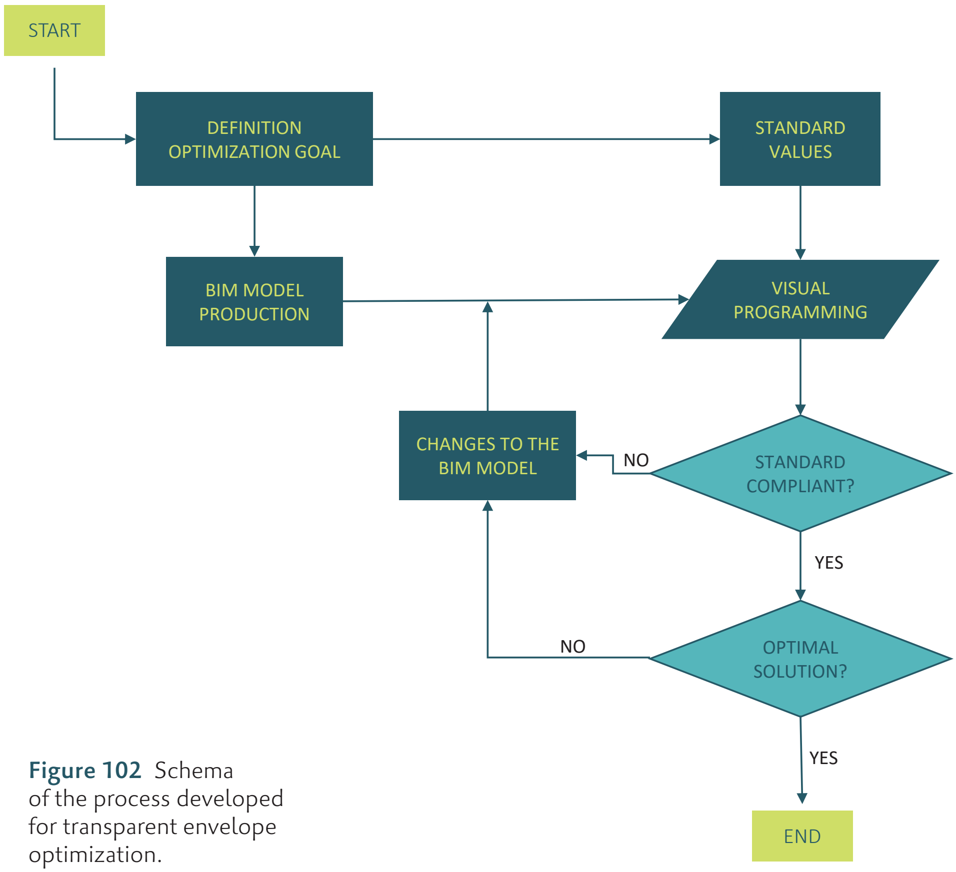


Figure 102 Schema of the process developed for transparent envelope optimization.

Tools The workflow is developed in Dynamo, a visual programming workspace, by connecting Nodes with Wires to specify the logical flow.

The workflow has five main groups of nodes, shown with different colours in Figure 103:

- an initial part allows to links the script to the BIM model and select a specific type of family, like "walls" in this example (blue);
- a part to analyse the model instances and extract the thermal transmittance data (green);
- a part to verify if the instance's thermal transmittance compliance with the standard value (prink);

- a part to analyse the instance and if there is an insulation layer a better solution, select it (orange);
- a final part allows creating the thickness increase routine until the condition is verified (purple).

In the orange part to identify the functions associated with each layer of the element, a node developed in phyton and available through a dynamo plugin has been modified and then used.

See the Appendix for an extended schema of the workflow.

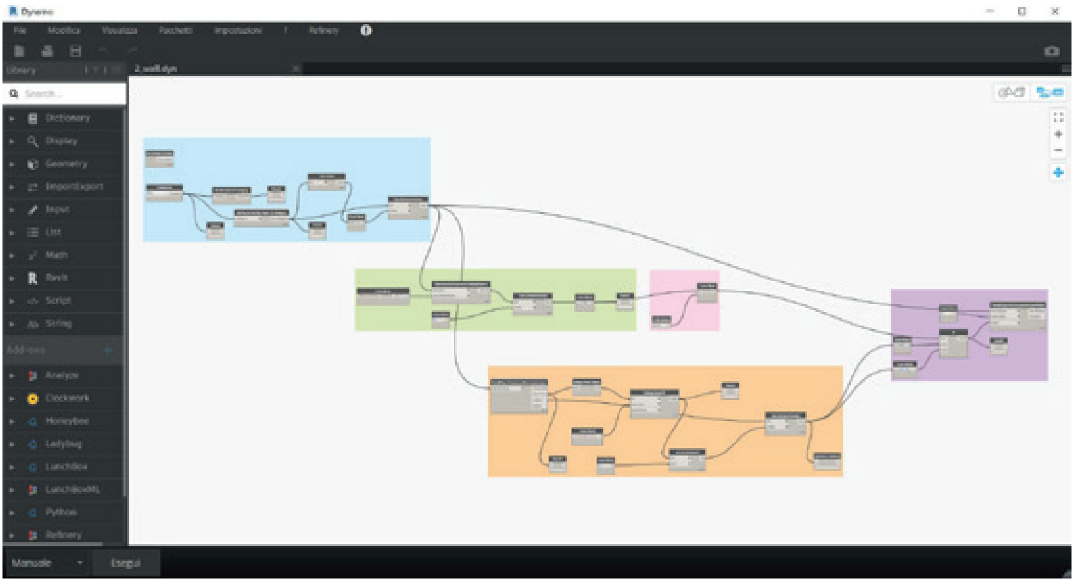


Figure 103 The Dynamo workflow developed. The different sections of the workflow are visible: BIM model (blue); instance data extraction (green); thermal transmittance compliance (pink); analysis of instance's stratigraphy (orange); thickness increase routine (purple) .

Final result The final result of the developed process is the digital model optimized concerning the chosen property of the vertical opaque elements, i.e. the thermal transmittance. Apparently, from a graphics point of view, there are no appreciable changes as the thickness of the vertical opaque elements is increased only by a few centimetres in some cases.

The described example was made on a case with a limited number of objects, and a specific property was selected. However, the process can be extended to more complex models, and both the parameter and the reference value used can be modified.

[3] Properties' optimization of the entire envelope

The third application example is the extension and merging of the two previous scripts to simultaneously optimize the properties of all building envelope elements, both opaque and transparent.

All the objectives, the starting models, the selected data, and the structure of the optimization processes have remained unchanged.

Tools The second script has been modified to use it with the other opaque elements of the construction, i.e. floors and roofs. Therefore, the transmittance limit values for these two types of elements have also been modified following the Ministerial Decree of 26 June 2015. The reference values used are 0.32 W/m^{2}K and 0.30 W/m^{2}K corresponding respectively to the floor and roof of a new building located in climatic zone D.

The first script has therefore been combined with the second, in the version extended to all three categories of opaque elements, walls, floors, and roofs. The new script is the one shown in Figure 104, the four groups of sub-processes corresponding to the four elements of the building envelope can see: the first group at the top is the script for the transparent elements while the three equal groups correspond to walls, floor, and roof.

The colours of the sub-groups correspond to:

- in blue the parts that allow to link the script to the BIM model and select a specific type of family;
- green and orange for the parts that allow to analyse the model instances and extract specific information;
- pink and purple are the colour of the groups of nodes that allow verifying compliance with set conditions or reference values.

Final result The final result of the process developed is the digital model optimized in terms of thermal performance, in terms of resistance and transmittance, of the entire building envelope. Apparently, from a graphic point of view, there are no appreciable changes as the windows and doors keep the geometrical dimensions unchanged while the thickness of the opaque elements is increased only by a few centimetres in some cases.

The described example was made on a case with a limited number of objects, and a specific property was selected. However, the process can be extended to more complex models, and both the parameter and the reference value used can be modified.

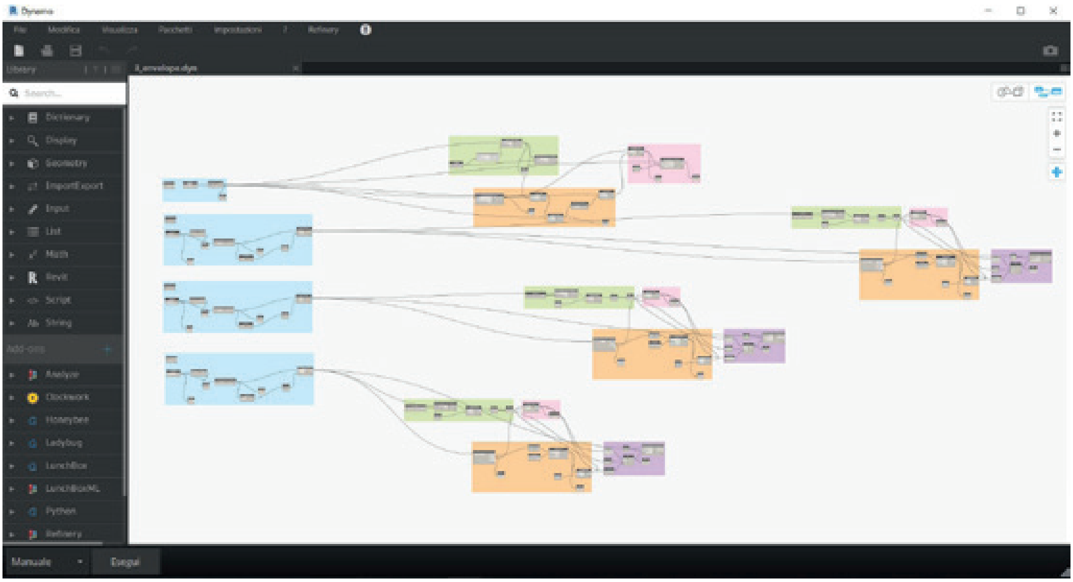


Figure 104 The Dynamo workflow developed. The workflow can be divided into the four main sub-flows for each type of envelope elements: windows, walls, floor and roof.

[4] Optimization of façade's geometry

Goal The fourth application example aims to optimize the solar radiation inside the building by changing the geometry of the façade cladding panels according to their exposure to the sun.

Digital Model The digital model used in this example is a volume created in Autodesk Revit (Figure 105). Contrary to previous models, the building is designed as a volume, or "mass", consisting of surfaces only and without specific information about the building envelope. The south-facing side on which the cladding will be applied has been deformed to have different radiation over the entire extension of the façade.

Data selection The information necessary for the development of this example is mainly three: the geographical location of the model from which the solar radiation information is derived; the surface of the digital model on which to apply the façade; the panel to be used. All this information is contained in the BIM model and can be used through the dynamo script. The model has been located in Italy in Genoa (Figure 106 a), and the selected façade is the curved ones facing south (Fig-

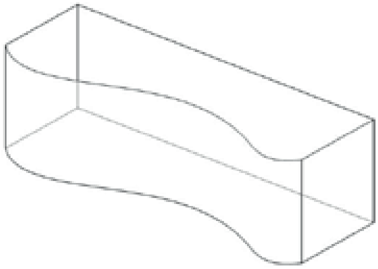


Figure 105 3D view of the digital model created in Autodesk Revit.

ure 106 b). The panel has been selected among the many available online databases and then imported in the Revit file. It is rectangular, and inside it, there is a square-shaped void. The two vertices of the short side of this rhombus can move along the diagonal of the rectangle to simulate its opening and closing (Figure 106 c).

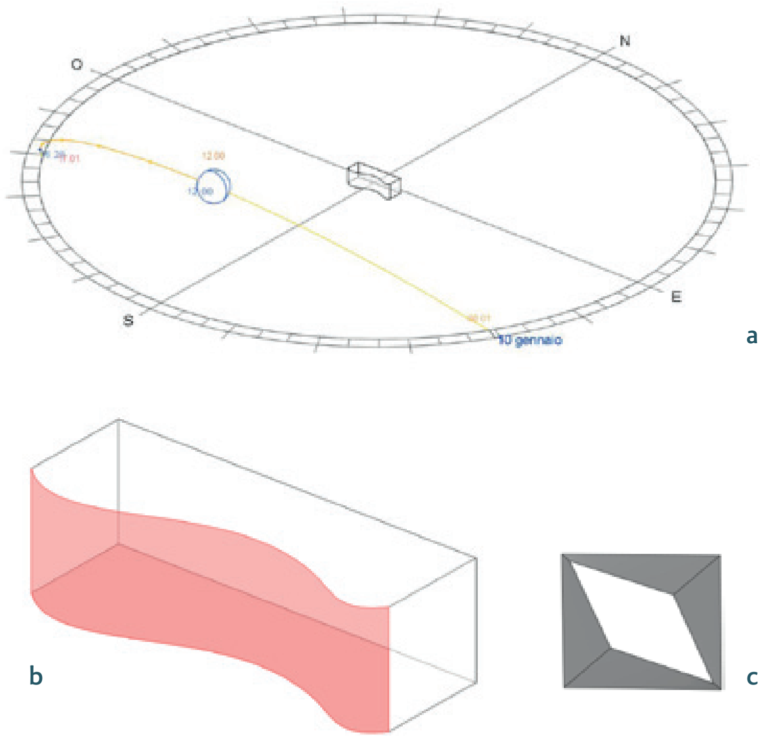


Figure 106 Detailed images of the information obtained from the BIM model.

Optimization process The optimization process has been structured in order to have maximum illumination through a curtain wall composed of partly opaque and partly transparent panels. After defining the objective, we move on to the creation of the BIM model, which is then connected to the visual programming program. The Dynamo workflow allows us to extract the position data and select the surface of the BIM model to be used. The script then allows to position the panels on the surface and modify their internal geometry. This last step is done by comparing the angle of incidence of the sun on the panel and its normal vector: the smaller will be its difference, the greater will be the opening of the panel to allow a higher amount of natural light to enter the building.

Tools The Dynamo's workflow has five main groups of nodes, shown with different colours in Figure 107 and more in detail in the Appendix:

- an initial part allows to links the script to the BIM model and select a specific surface, like the south one in this example (light blue);
- a part that allows to select the position of the model and the sun details (blue);
- a part to create a grid on the surface in order to place the entire façade (green);
- a part that allows to select the panel and place it on the created grid (orange);
- a final part allows changing the geometry of the panel based on solar radiation (pink).

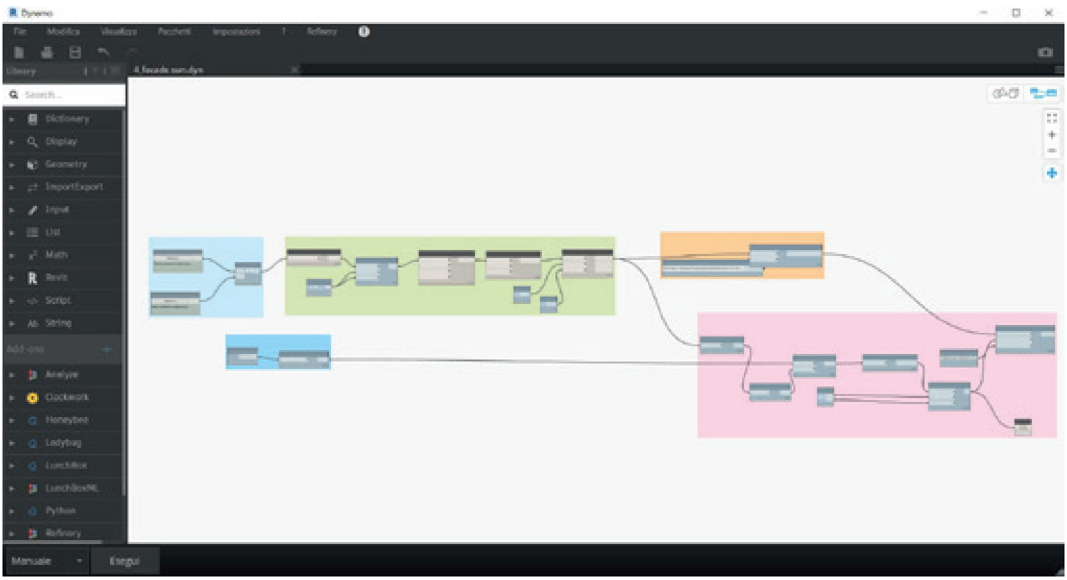


Figure 107 The Dynamo workflow developed. The different sections of the workflow are visible: BIM model (light blue); surface subdivision (green); BIM model position (blue); panel's selection (orange); panel's façade geometry (pink).

Final result The final result obtained is the cladding of the selected south wall with panels of different geometry according to the solar incidence (Figure 108). The example described was carried out on a single surface and using panels with a specific geometry. However, the process can be adapted for models, surfaces, and panels with different geometries.

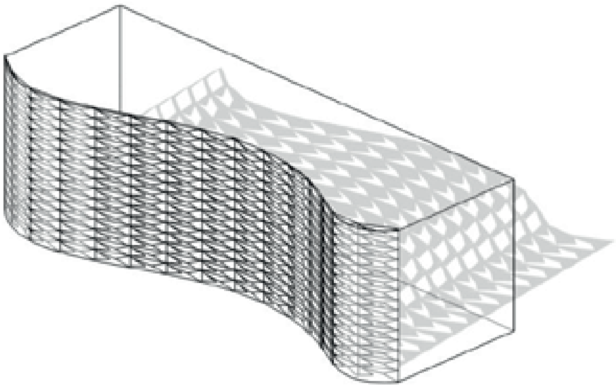


Figure 108 BIM model on which a cladding has been realized on the south wall with panels with variable geometry.

[5] Volume and solar radiation optimization

Goal The fifth example aims to optimize the building's compactness ratio and solar radiation on the vertical walls. Specifically, it was decided to minimize the S/V ratio between the building's dispersing surface and its volume by freely varying the dimensions of width, length, and height of the starting volume up to a limit set at 100m. The solar calculation was made considering the climatic data for the year 2018.

Digital Model The digital model used in this example is a cube created in Autodesk Revit (Figure 109). Like the model in the previous example, the building was designed as a volume, or "mass," consisting of surfaces only and without specific information about the building envelope. The starting cube side is 10m.

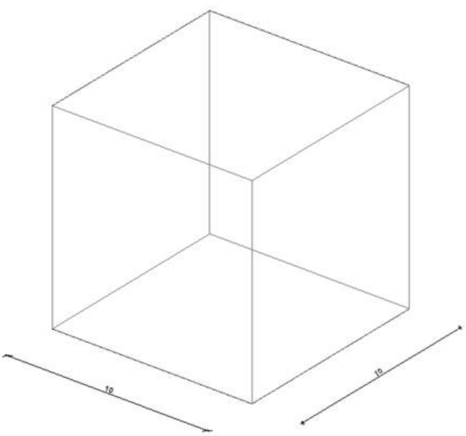


Figure 109 3D view of the digital model developed in Autodesk Revit.

Data selection The information needed for the development of this example is mainly the geographical location of the model, from which the information on solar radiation and geometric characteristics are derived. All this information is contained in the BIM model and can be used through the dynamo script. The model has been located in Italy in Genoa, and the Revit file database contains the climatic information of this location.

Optimization process The optimization process has been structured to achieve the objective set through the use of genetic algorithms.

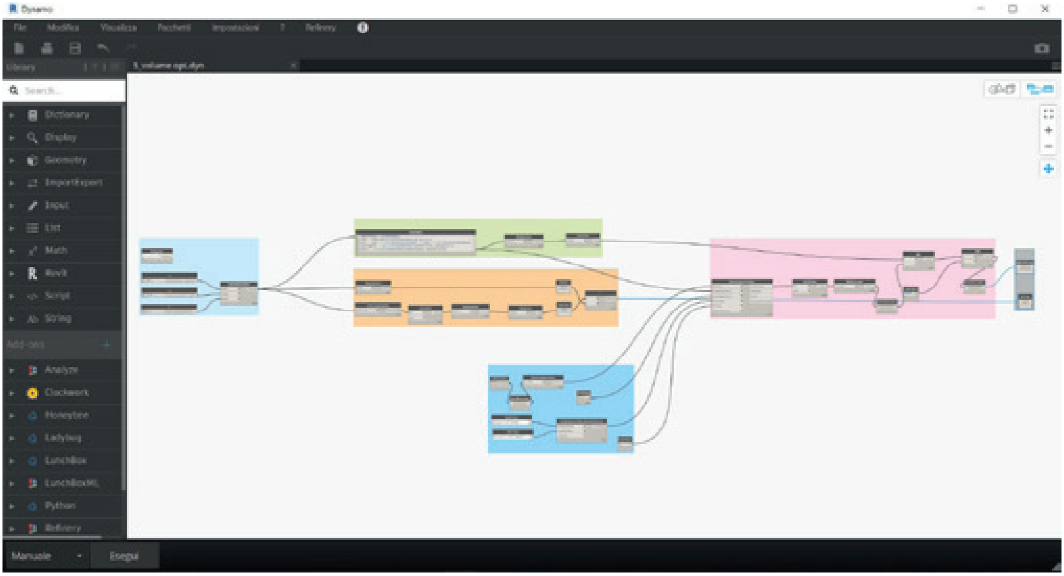
The BIM model is linked to the visual programming program that permits to calculate the S/V ratio and to calculate the amount of radiation on the vertical surfaces of the volume based on climate data for the chosen year. This information is then further entered into the optimization program through the use of genetic algorithms able to calculate all possible solutions based on the data and constraints set.

Tools The first tool used is Dynamo, a visual programming workspace, by connecting Nodes with Wires to specify the logical flow. The workflow developed has five main groups of nodes, shown in Figure 110 and Appendix:

- an initial part allows to links the script to the BIM model and select the solid (light blue);
- a part to extract the geometry information of the selected solid and to fix the range of variation of the dimensions of the solid (green);
- a part to calculate the S/V index (orange);
- a part that allows to select the position of the model and the sun details (blue);
- a part to calculate the solar radiation on the vertical surface of the selected solid (pink);
- a final part collects the two values that will be respectively minimized and maximized, S/V and cumulative solar radiation (grey).

Then the script is exported to be used in Refinery, a dynamo plugin still available in beta version, that allows using genetic algorithms, in particular, the NSGA II described in chapter 4. Refinery allows to fix some settings of the optimization process before starting (Figure 111):

- inputs that could be used and modify. In this example, they are the three main dimensions of the solid;
- outputs that could be used as goals of the optimization process. In this example, the outputs are S/V and cumulative solar radiation values;



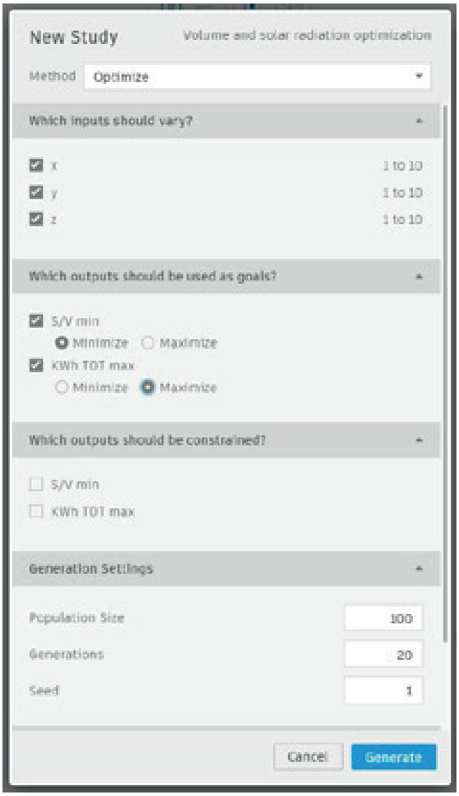


Figure 110 The Dynamo workflow developed. The different sections of the workflow are visible: BIM model (light blue); geometry information extraction (green); calculation of the S/V index (orange); BIM model position (blue); calculation of the solar radiation (pink); optimization's value (grey).

Figure 111 Picture of calculation settings in Refinery tool.

- add any numerical constraints to the output values if they have not already been set in the dynamo workflow;
- generation setting of the GA used: number of individuals in the initial population, number of generations, and number of the starting point called "seed". In this example, the values chosen respectively are 100, 20 and 1.

Final result The final result obtained through the use of genetic algorithms is a series of possible solutions to the objective set. In Figure 112, some of the results obtained are reported. Among all the possible solutions, the decision-maker can choose the final one that can then be re-imported into Dynamo and Revit, to modify the starting model with the optimized information. The example described can be expanded and reused in other cases, modifying the starting volume and the surfaces on which to calculate the irradiance, and different constraints and ranges of possible variation of the input data can be inserted.

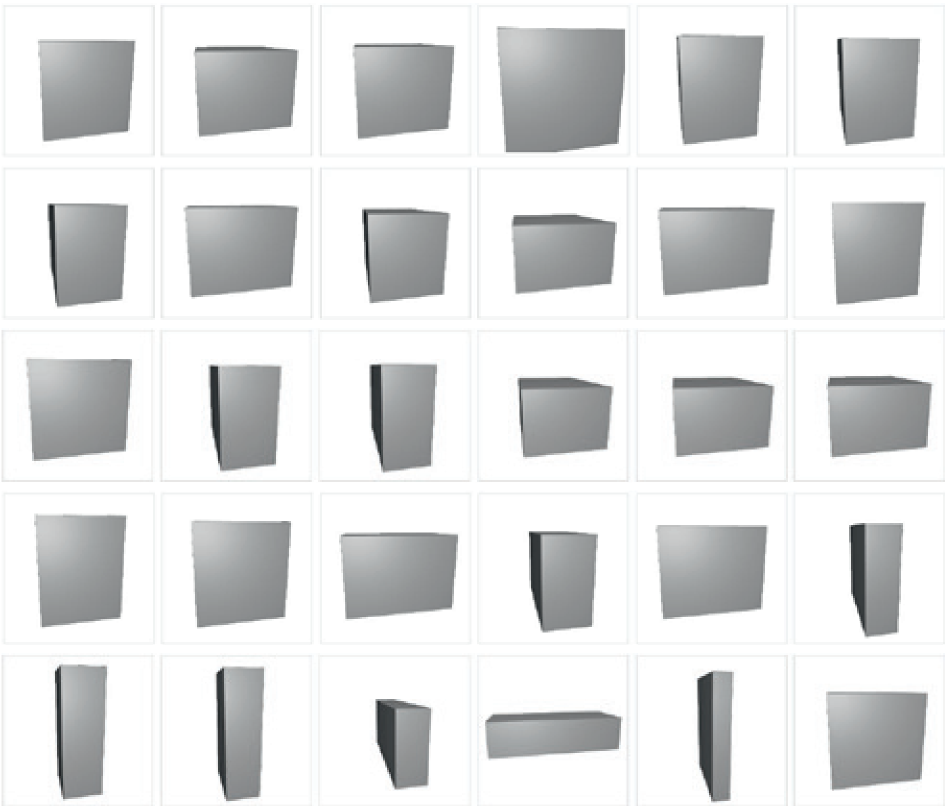


Figure 112 Some of the solutions obtained through the use of genetic algorithms.

[6] Selection of the best solution using attributes

Goal The sixth application example was developed for the choice of the optimal solution among several options based on attributes. As shown in the previous example, all the solutions obtained with Refinery are "excellent" because they are already the result of an optimization process carried out with genetic algorithms. Therefore, in cases like this, the decision-maker is once again called to make a choice.

This situation is similar to the one that designers have to face in case of redevelopment projects. Once certain constraints have been set, such as the budget available and the energy performance to be achieved, multiple solutions can be identified, all equally valid. In all these cases, decision theory and multi-attribute methods, described in Chapter 4, can be a valuable aid in identifying the optimal final choice.

Digital Model The example deals with a practical case of a redevelopment project of an existing building in which the designer is called to choose the optimal intervention among ten possible valid solutions. A digital BIM model of the entire building was created with Autodesk Revit (Figure 113). The model was then exported in .ifc format to be inserted in an energy simulation software under Italian regulations and calculation procedures and with which the final energy consumption of the building can be calculated after the application of each solution.

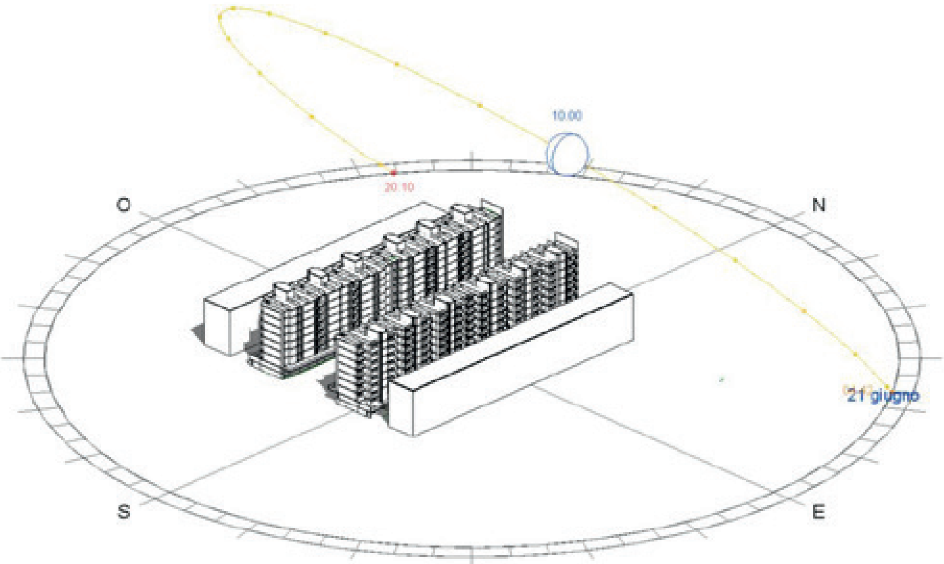


Figure 113 3D view of the digital model developed in Autodesk Revit.

Data selection The interventions identified were analysed based on four attributes: cost, performance index, durability, and feasibility. Each solution was simulated and studied separately based on the established attributes. The data obtained were collected from the different software, and the analyses carried out and inserted with a non-automated procedure in an Excel spreadsheet in order to construct the decision matrix [m,n] (Table 2).

Table 2 Matrix of decisions of a multi attribute problem.

		Total cost [€]	Energy index	Durability	Feasibility
1	Thermal insulation - first floor	104316	118.91	Good	Ease
2	Thermal insulation - roof	94381	119.16	Good	Ease
3	Thermal insulation - façades	284738	118.89	Good	Difficulty
4	Thermal insulation - walls/ floors - heating zones/ no-heating zones	276430	111.24	Good	Ease
5	Thermal insulation - walls/ floors - no-heating zones	137651	118.62	Good	Difficulty
6	Windows Substitution (EAST side – Heating zones)	346675	106.41	Good	Ease
7	Windows Substitution (WEST side – Heating zones)	771023	87.81	Good	Ease
8	Windows substitution (no-Heating zones)	170957	118.39	Good	Ease
9	Generation Plant substitution	25000	103.44	Good	High Ease
10	Generation Plant substitution and regulation system installation	88920	78.99	Good	Ease

Optimization process The optimization process is based on the choice of the optimal solution using the TOPSIS method, belonging to the category of MADM. This method has been used because it is the one with the least degree of objectivity and allows more easily to arrive at an optimal solution.

Tools The tools used to calculate the optimal solution were two: Excel and Matlab. The first tool was used to collect data and build a decision matrix. Before using the matrix, it was converted into numerical values only. For this purpose, criteria were established to transform the attributes of durability and feasibility. Specifically, the following conversion table was used:

DURABILITY		FEASIBILITY	
no sufficient	0	no feasible	0
poor	1	high difficulty	1
mediocre	2	difficulty	2
good	3	ease	3
high	4	high ease	4

Subsequently, the decision matrix was imported into Matlab. Within this program, the following steps of the TOPSIS method for solving the problem have been written:

```
function [ S, I ] = topsis(matrix,weight)

[m,n]=size(matrix);
A=normc(matrix);
normp=norm(weight,1);

for j=1:n
   v(j)=weight(1,j)/normp;
end

for i=1:m
   for j=1:n
      T(i,j)=v(j)*A(i,j);
   end
end

Aw=min(T);
Ab=max(T);

for i=1:m
   dw(i)=norm(T(i,:)-Aw);
   db(i)=norm(T(i,:)-Ab);
end


for i=1:m
   s(i)=10*dw(i)/(dw(i)+db(i));
end

[S,I]=sort(s);

End
```

Final result The final result obtained is the following list of possible solutions ordered from the closest to the ideal solution to the farthest one and the indication of the distance in percentage (Table 3).

Table 3 Final results obteined using TOPSIS method.

9	Generation Plant substitution	93%
10	Generation Plant substitution and regulation system installation	74%
2	Thermal insulation – roof	72%
1	Thermal insulation - first floor	71%
8	Windows substitution (no-Heating zones)	68%
4	Thermal insulation - walls/floors	
	heating zones/ no-heating zones	60%
5	Thermal insulation - walls/floors - no-heating zones	56%
6	Windows substitution EAST side – Heating zones)	54%
3	Thermal insulation - façades	46%
7	Windows substitution (WEST side – Heating zones)	25%

This result allows the decision-maker to have the solutions sorted according to the chosen attributes and to identify an "excellent" final solution that comes closest to the set objective.

The example described has been presented on a specific decision matrix but can be used to solve any other problem with the same characteristics and can be formulated with a decision matrix consisting of the solutions and attributes identified.

CONCLUSIONS 6

6.1 Final Considerations

The goals of sustainable development require a significant commitment from the construction sector, as the environmental, social, and economic impacts generated by it are also significant. All activities and people working in this sector are called upon to actively contribute to the global challenge for adaptation and mitigation to climate change. Therefore, designers, moving in a context-oriented towards a resilient future where resources (energy, raw materials, economic, etc.) are limited, need to find new strategies to achieve an "optimized result".

The research work presented here has been conducted through the study and in-depth analysis of the state of the art of the three chosen areas of investigation: sustainability, digitization, and optimization. The second chapter dealt with the topic of sustainability, starting from the most recent data on the current situation and global initiatives to tackle climate change to the strategies adopted in the construction sector and specifically in sustainable design. The study since the fourth industrial revolution described in chapter three has allowed us to outline its principles, potential, and weaknesses. Thanks to this study, it has been possible to identify the technological innovation that can contribute to a radical transformation of the construction process: Building Information Modeling (BIM). The study of optimization techniques to manage the complexity of design choices has been reported in chapter four. We started from some historical hints of its development and the first optimization experiences to arrive then to the applications in the construction context and specifically to the most used techniques in the design field.

The objective of the research was to take inspiration from these analyses to imagine possible virtuous complicity between sustainable objectives and the potential of the digital revolution, supported by the operational characteristics of optimization methods. The intent was to identify a new way to respond in the field of construction to the global challenges of sustainable development to which we are all called. There is much potential for improvement in the construction sector if we consider that despite the wide variety of existing tools and the shared awareness of the importance of doing something about climate change, not all teams of architects use them or if they are used, mostly as tools for post-design assessment. Several studies have shown the potential to support optimal design decisions and that around 20% of design decisions made in the early design phase represent 80% of the total impact on the final energy performance of the building. Although all recent technological innovations are vehicles of many benefits, they also have practical and economic limitations that limit their use and diffusion. There are also multiple risks, some of which have not yet been adequately addressed and explored, such as security, privacy, user protection aspects, or management of the enormity of the data produced.

The Building Information Modeling was chosen as the digital environment and tool with which to develop the proposed methodology. BIM can reduce some of the critical issues generated by a "group of experts" who collaborate in a project. First of all, the necessary information collection for the simulation and evaluation of the project choices to be adopted. The possibility to work with a digital twin of the built is an essential innovation of the process, and the data contained in the Common Data Environment (CDE) are the heart of BIM. However, there are still several challenges to use BIM and CDE to manage all aspects of sustainability. From a theoretical point of view, it is already considered possible, but, in practice, there are still no standardised procedures and consolidated tools for the management of BIM 7D data and information. In fact, for the seventh dimension of BIM, defined by the Italian standard UNI 11337-1 as the seventh dimension related to the simulation of the work or its elements according to the sustainability (economic, environmental, energy, etc.) of the intervention, there are not yet available and consolidated applications and tools. Another element that shows how this area is still little explored lies in its association with a BIM dimension. In this research work, it has been chosen to refer to sustainability as BIM-7D. However, there is still confusion and uncertainty in the references, and, in different contexts from the Italian one, it is associated with BIM-6D. This fact highlights even more how this level has not yet been reached and this information is not yet fully managed in the BIM building process.

This gap between reference literature and work practice is a recurrent element in BIM, as it has been possible to ascertain also thanks to the comparison with the interviewed experts. Not only with regard to aspects related to sustainability but more generally there are many differences when studying and analyzing the different national contexts and the different professional realities related to small and large scale projects. It is expected that soon this fragmented picture of Building Information Modeling, the result of the different sensitivities of government agencies and individual professionals, will be smoothed out by the recent ISO 19650:2018 - Organisation and digitisation of information on buildings and civil engineering works, including Building Information Modeling (BIM). The standard primarily aims to reorganise all existing standards by providing a single internationally valid definition for the exchange of data and establishing standard protocols for information sharing between the various stakeholders in the construction industry. Secondly, this new legislation may also be the inspiration and support needed to trigger a renewal process in those countries that are less advanced in construction 4.0.

In the Italian context, the introduction of the BIM Decree and the request to use digitized systems in public procurement is a clear signal of thi expected change. The direction adopted and the willingness to undertake a renewal process by exploiting the potential of BIM will lead first of all to rationalize and make more efficient the timing and methods of the now obsolete tender procedures. Besides, the dissemination of BIM will also bring with it the increase in the skills of professionals and progress in the development of existing tools that will facilitate its use in several aspects of the design process.

In the second part of chapter five, the final elaborations and considerations of the research work have been "translated" into an operational strategy that would support designers to achieve sustainability goals. In particular, a replicable procedure has been developed for the optimization of sustainable project characteristics. This strategy is a sequence of steps able to include sustainability parameters as a design criterion fro the very beginning phase, using a digital model developed in the BIM framework, arriving at the optimal choice of design solutions through decision-making methods.

In the development of this procedure, attention is paid to the choice of intervention strategies aimed at achieving the objectives of the project itself, minimizing the dispersion of information and improving collaboration between the various specialists involved. Specifically, it is a sequence of steps to be able to include sustainability as a design criterion from the very beginning, using a digital model developed in the BIM field, to then arrive at the choice of optimal solutions thanks to the use of decision theory.

The methodology has been tested through some application cases presented in paragraph 5.5. The diverse examples have shown how it can be used to organize and sequence the phases leading to the identification and choice of the optimal solution based on the objectives set. The case studies did not aim to cover the full range of possible design choices but, starting from some simple elements, to highlight their adaptability and replicability to more complex situations with different objectives and information available.

The design process is also subject to time constraints, and designers must make decisions quickly. The use of software certainly helps to speed up the process, but the creation of parametric models takes time. BIM has undoubtedly proved to be a useful tool, not only because of its parametric nature but also because it allows us to quickly capture any changes and information that could be made and added by designers at any time, without the need to completely rewrite and redo the model. Nevertheless, the implementations of the methodology have shown that many skills in BIM modeling and visual programming are needed and must be developed from time to time based on the problem to be addressed. The dependence on the designer and his skills is evident, as it was also in the research path. That is a limit that must and will be overcome thanks to the spread of these tools; in fact, some of those are still in beta version, updated continuously and modified.

In the future, the potential highlighted by the synergy between sustainability and the digital revolution, supported by optimization methods, could be the answer in our sector to the increasingly stringent demands of regulations and customers on the requirements and performance in terms of sustainability of construction. The proposed methodology highlights how these elements can be put together and used by designers who will have to operate in this new scenario. The examples of implementation, emphasize how the methodology, starting from single construction elements, can be used up to the scale of the building or neighbourhood to address the real decision-making problems in sustainable design.

6.2 Future Developments of the Research

The future developments of the research carried out are many and can be traced both to more general aspects and to more particular and specific ones concerning what has been studied and developed.

The research approach based on three main topics was carried out similarly and methodically, proceeding in the study by levels. This chosen approach leaves ample room for development since many aspects have been excluded because of the chosen key, and even each topic can be a separate subject of study. In particular, it was decided to limit the definition of state of the art in order to have a more complete and homogeneous picture of recent developments and advances in the study topics. The areas of research on sustainability, digitization, and optimization have developed at different times and are also associated with different fields of application. Therefore, changing or eliminating this approach, and this time boundary would allow for a different and broader view, and consequently, new research considerations and results may emerge.

The detailed study of a specific aspect of each topic has determined a choice that has led to the consequent natural exclusion of countless other instruments, principles, methodologies. For example, in the case of digitization, an area still in full development and constant mutation, among all the possible technological innovations, Building Information Modeling was chosen as the optimal environment for the achievement of research goals. Other interesting aspects have been omitted only partially explored in the field of construction, such as Big Data, which could give light to further developments in the already existing information management skills of BIM. Alternatively, in the same way concerning sustainability, many objectives can be chosen for optimization processes.

The choice to dialogue and discuss with experts on three topics studied was motivated by the need to expand the research area. The different points of view heard allowed the emergence of real challenges and difficulties that are found in everyday practice and that limits the application of the investigated aspects in design processes. The interviews, limited to a restricted number of candidates, could be extended in order to collect more information and define an increasingly detailed picture.

The implementation part of the research can also be expanded, using the reported examples as a starting point for the development of new optimization processes. As shown, the implementations have been described with the intent to highlight the applicability of the proposed methodology. Several factors, however, may affect possible developments, such as the user's skills and competences, software and application development, the availability and management of information of the digital model to be used. The overcoming of these practical limits could lead to a real possibility to use this kind of approach in a design project, based on the optimization processes developed in a BIM environment. The proposed methodology would make it possible to achieve a general and coordinated optimised workflow between the different actors involved in the process, including aspects concerning the achievement of sustainable development objectives.

At the end of this PhD research, it can be said that the challenges for sustainable development and the digital revolution are profoundly changing the construction sector. Many signs of innovation have been highlighted through the presented investigations. However, in the near future, other profound transformations will be required, which will involve substantial economic investments, increased technical expertise, and a global innovation of the construction sector at all stages. The presented research work has contributed to delineate the current situation in the construction sector and o trace a possible course through the synergy of the three key concepts: sustainability, digitization, and optimization. This approach can be considered as a valid starting point for an area that is still not much explored, but that could be developed in the near future to face the global challenges of sustainable development.

APPENDIX 7

INTERVIEW GUIDE

Introduction

The goal of the interview is to highlight the current issues the construction industry faces and how digitization can help address them. BIM is often held up as the gold standard for digitized construction, yet the construction industry as a whole has been slow to adopt the BIM process. We are, therefore, interested in understanding the barriers and facilitators to BIM adoption – in particular, concerning energy optimization and sustainable performance simulation. The aim is to examine the role of BIM in transforming construction work and solving the environmental challenges related to the consumption of energy and primary resources in building construction and use. More specifically, we are interested in understanding how well BIM supports the work practices of performance optimization.

General questions for understanding the interviewed person

Name:
Company:
Role:
Experience (years):
Field and kind of your work:
What kind of project/work do you work on?

Questions about BIM

- **How do you understand BIM?**
  - Technology or process?
  - When is it relevant to use BIM?
    - Probe for comparison with CAD and other digital tools
  - What do you see as the main barriers, drivers, and benefits associated with BIM?
    - Probe for examples

- **Does your company use BIM?**
  - *If yes*, what is your own role in the BIM team? Specialist, coordinator, manager...?
  - What are the other digital and non-digital tools used besides BIM?
    - Probe for what role the different tools play
  - Do you use a "Plan of Work"? Do you have your template, or do you use an already existing one?
  - How are the different specialists collaborating in BIM?
    - Probe for how they share their information (upload local models?)
  - How do you decide when it is relevant to use BIM as a tool or not?
    - Probe for a recent example
  - In which phases of the construction project is BIM most relevant?
  - How many in your company work directly in BIM (estimate)?

- **Do you use BIM for renovation projects?**
  - *If yes*, how do you collect the necessary data for the BIM model?

- **From your experience, in a collaborative process with several partners, what are the pros and cons of BIM?**
    - Probe for an example of a situation where s/he successfully used BIM
    - Probe for an example of a situation where it turned out to be problematic to use BIM

Questions about building performance simulation

- **What do you consider as the main practices involved in energy simulation?**
  - What are the main difficulties involved in doing energy simulations?

- **Does your company provide energy simulation and optimization studies?**
- **At what stage of the project do you carry them out?**
  - Before or after the decisions become irreversible?
  - How are the results used to guide project choices?
    - Probe for an example

- **Do you have parameters to assess the quality of the project? Or Indicators to evaluate the design ideas?**
  - How are these parameters decided on?
  - Who defines them?

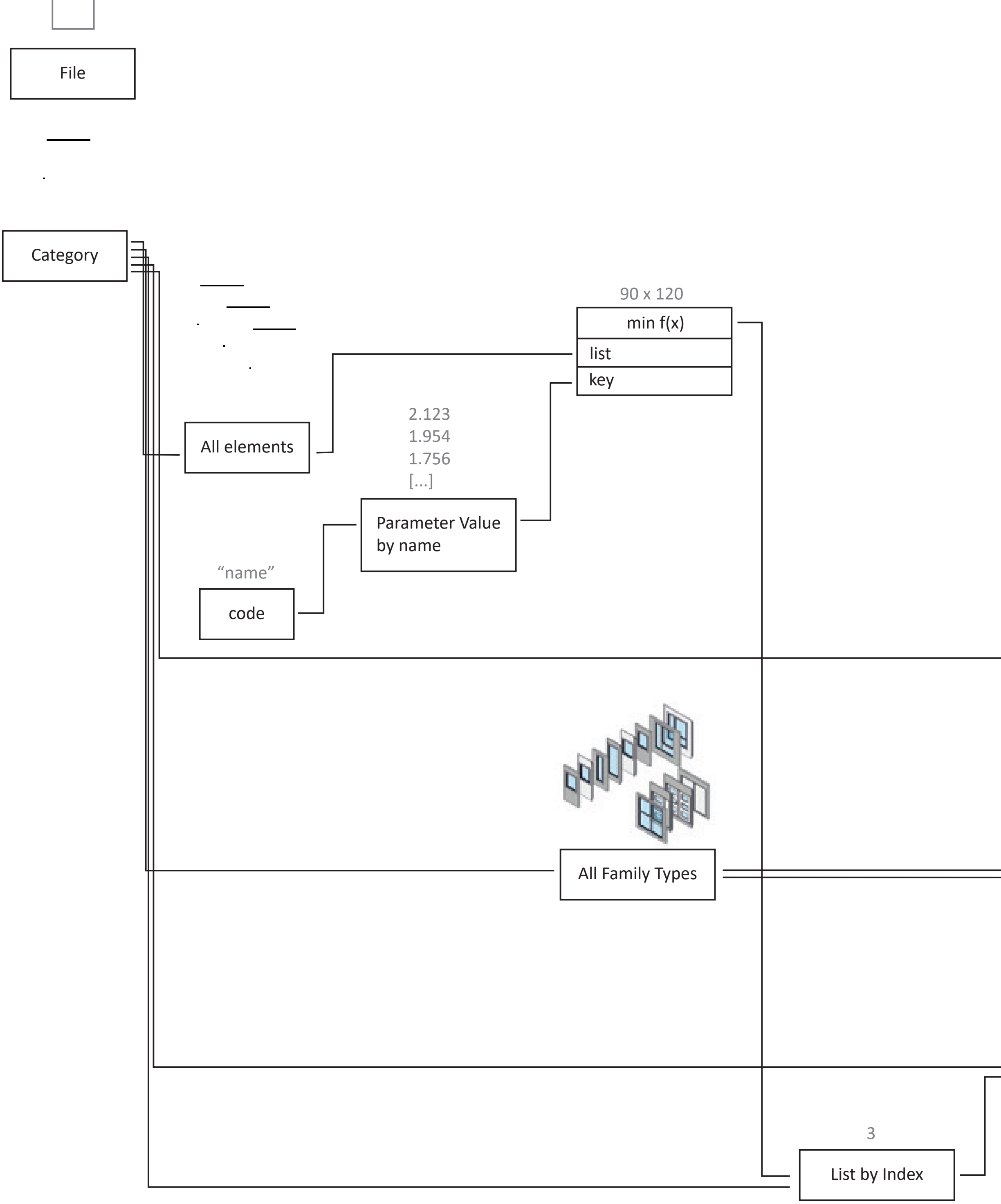
- **In your opinion, what are the best tools for performance optimization, and why?**
    - Probe for examples

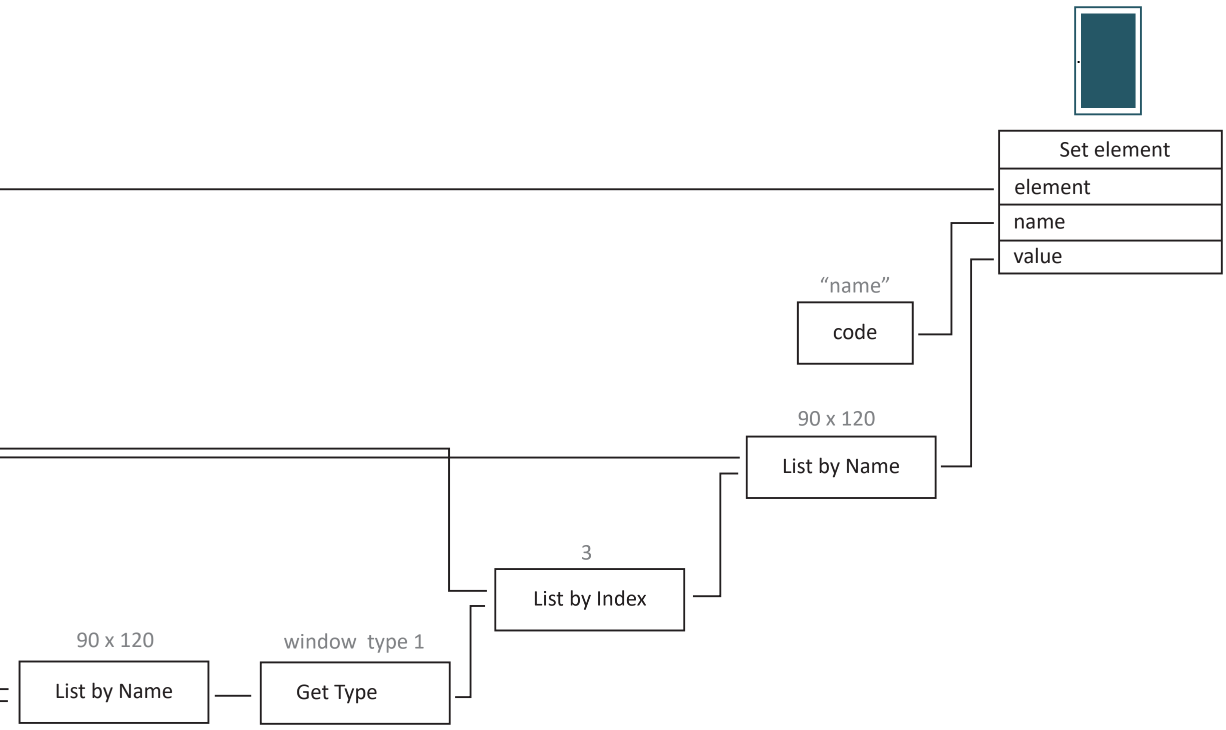
- **Do you use BIM tools for optimization, and in what kind of projects?**
  - *If yes*, what are the main benefits?
    - Probe for examples
  - When do you avoid using BIM for optimization? Why?

- **When collaborating with others, what is most important to communicate from the perspective of optimization?**
    - Probe for examples of communication failures
    - Probe for the impact of communication practices on workflow and quality

Do you have any further comments?

[1] Properties' optimization of the transparent envelope

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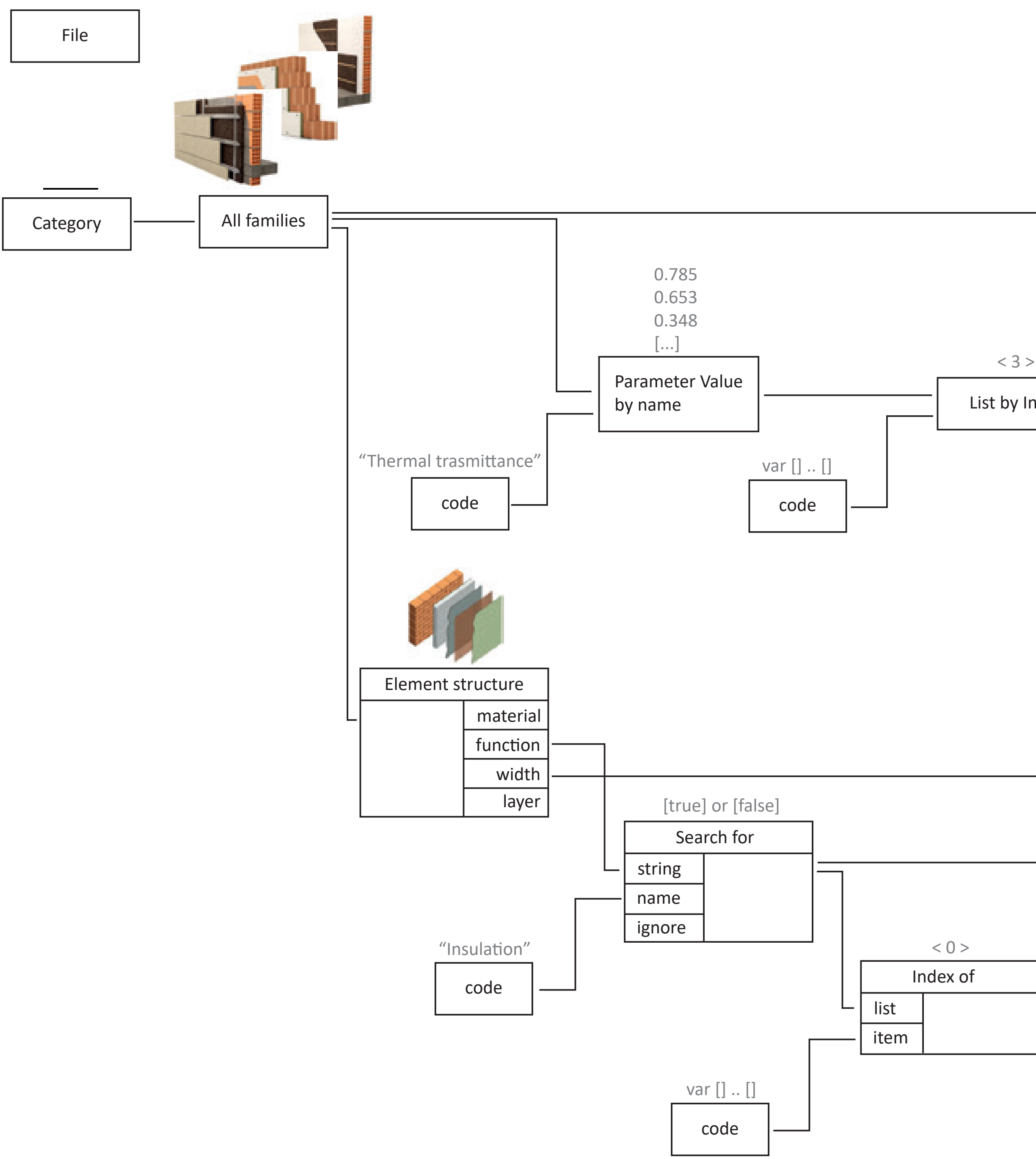
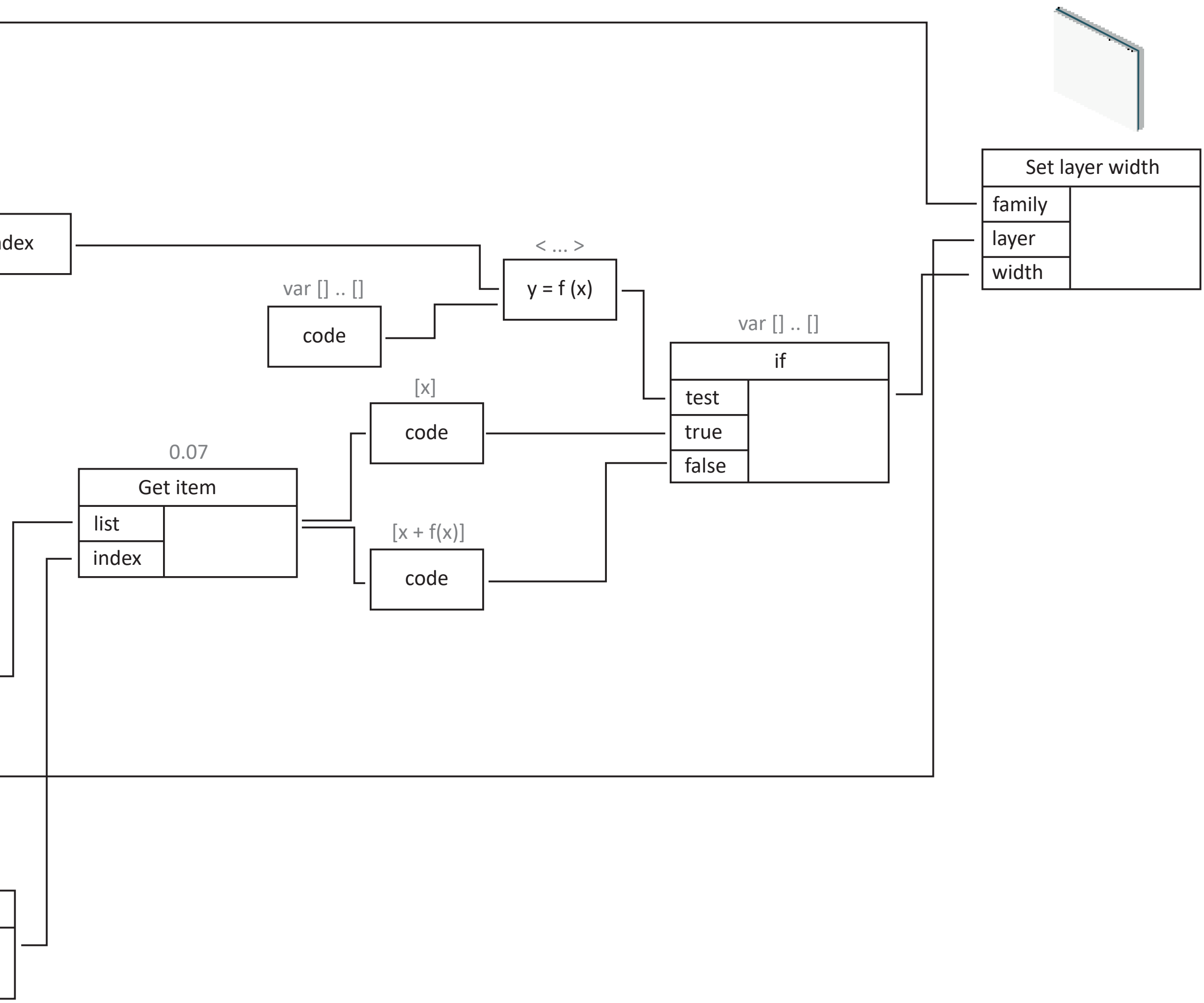
[2] Properties' optimization of the opaque envelope





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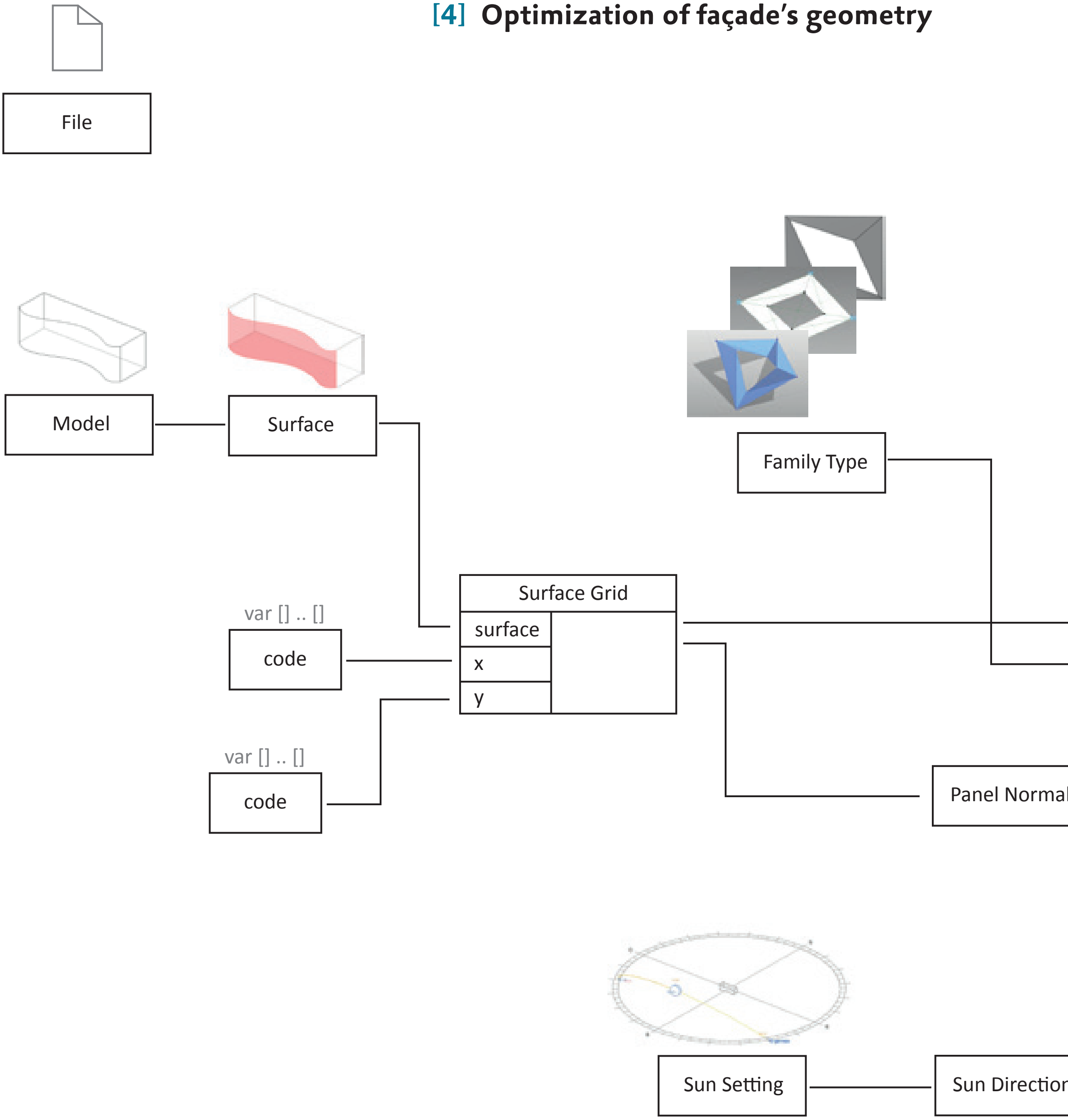
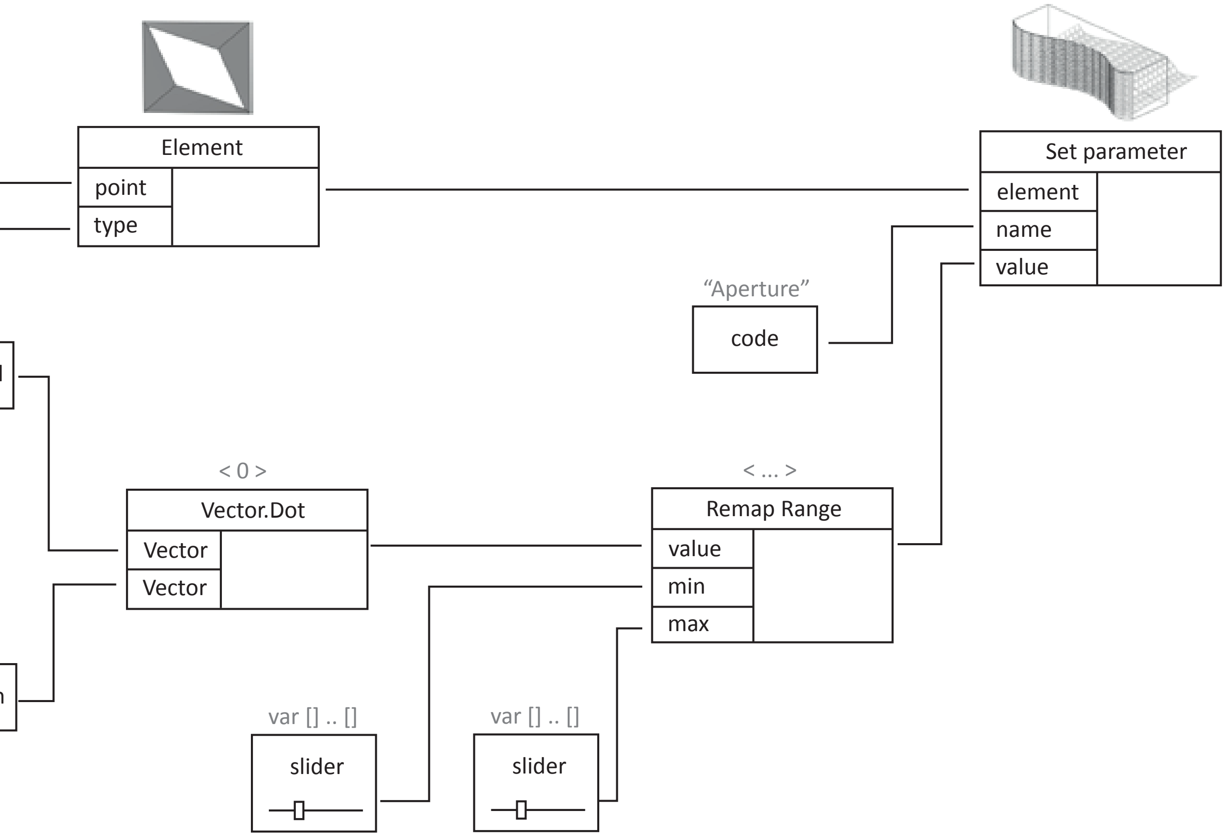
[4] Optimization of façade's geometry

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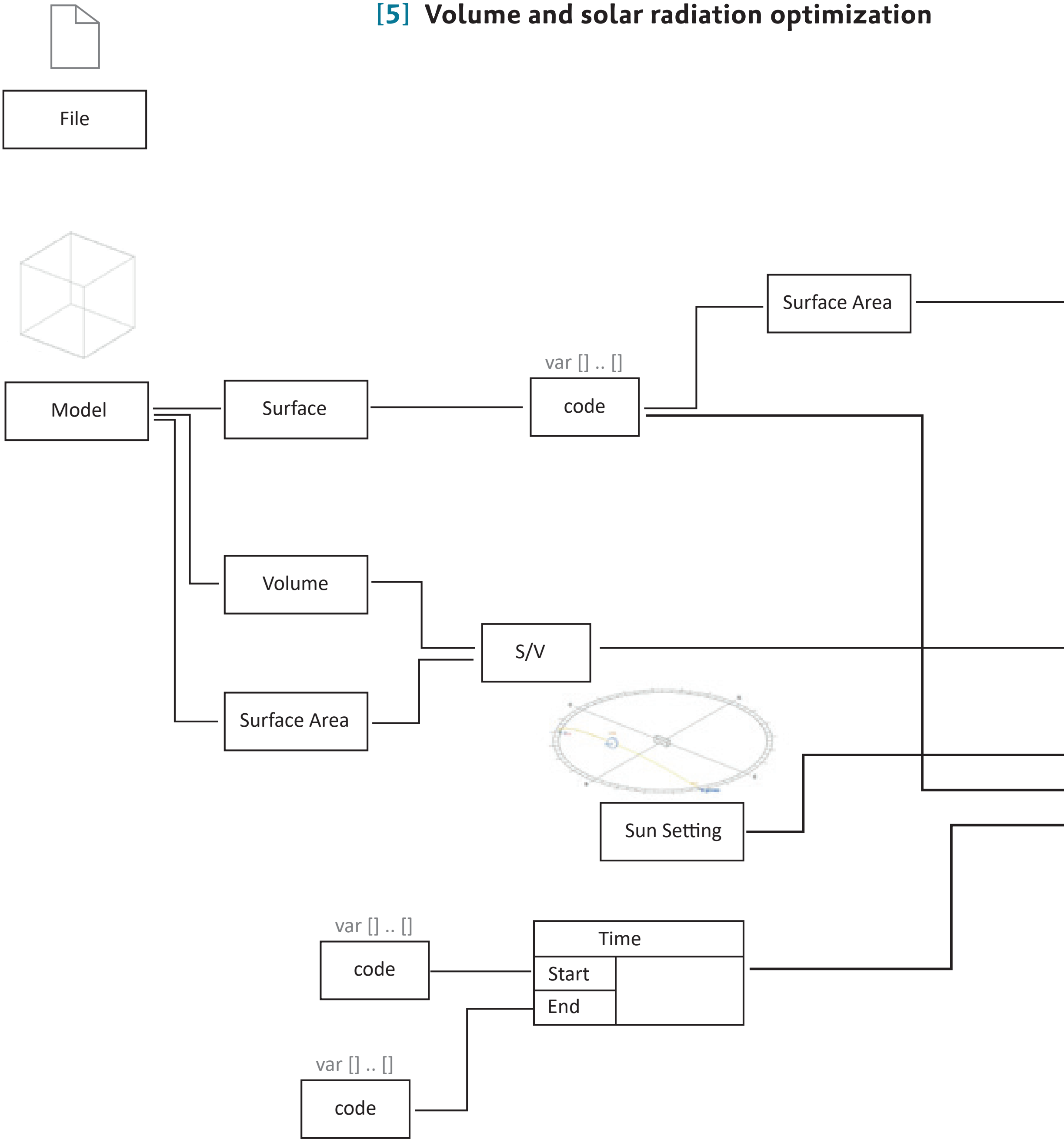
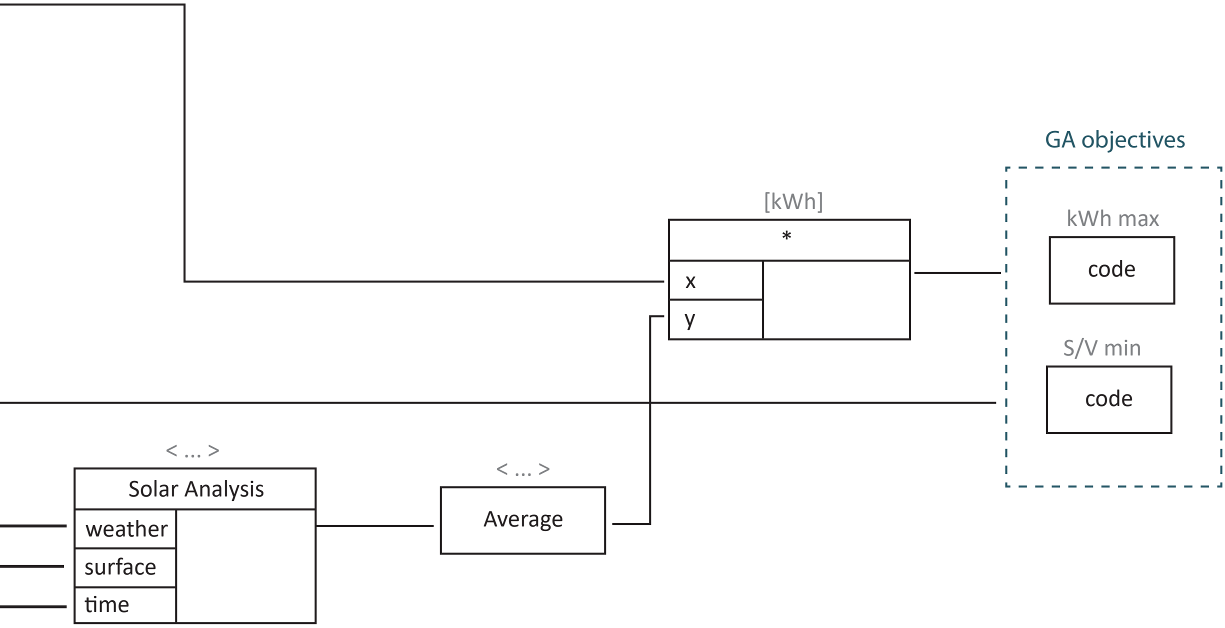
[5] Volume and solar radiation optimization

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